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A PILOT STUDY OF THE IRREGULAR WINDS AT CHEMICAL RELEASE ALTITUDES

C. G. Justus

J. B. Montgomery, III

Space Instruments Research, Inc.
Atlanta, Georgia 30313

Contract No. F29601-68-C-0040

TECHNICAL REPORT NO. AFWL-TR-68-132

May 1969

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

This report was prepared by Space Instruments Research, Inc., Atlanta, Georgia, under Contract F29601-68-C-0040. The research was performed under Program Element 61102H, Project 5710, Subtask 07.003 (RHA 3061), MIPR 528-66, and was funded by the Defense Atomic Support Agency (DASA).

Inclusive dates of research were 3 January 1968 to 3 October 1968. The report was submitted 24 February 1969 by the Air Force Weapons Laboratory Project Officer, Captain Joseph S. Greene, Jr. (WLRT).

This technical report has been reviewed and is approved.

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ABSTRACT

Results are presented of a study of the irregular horizontal and vertical winds observed from chemical clouds released on 16-19 November 1966 from Yuma, Arizona; on 17 November 1965 from Barbados, West Indies; and on 17 May 1963 from Eglin Air Force Base, Florida. The vertical wind data showed that vertical motion does not occur in such a way that as cloud points move up or down they would tend to alter their horizontal motion so as to adjust to the mean wind profile. It was found, however, that the horizontal wind profiles tended to change with time in such a way that the altitudes of constant speed would shift up or down in a similar manner to the vertical movements of cloud points. The altitude variations of constant speed points throughout the nights of 16-17 and 18-19 November at Yuma were found to be smaller in magnitude than the vertical motions of the cloud points over short periods. The 24, 12, and 8 hour period tides were computed for the 16-19 November 1966 Yuma data. Tidal winds and the irregular horizontal residual winds are reported. The rms irregular winds computed by a day-to-day difference method are also presented. Structure functions of the horizontal irregular winds exhibit a 2/3 power law with respect to both time variation and horizontal displacement. However, the vertical structure function of the horizontal irregular winds is found to follow a power law with an exponent value of 1.4. Some suggestions for further study are given.

(Distribution Limitation Statement No. 1)

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SECTION I

INTRODUCTION

Atmospheric winds have been studied for several years by the use of high altitude gun-launched ballistic probes fired from a 16-inch gun at Barbados and, more recently, Yuma. These experiments have been conducted by the U. S. Army Ballistics Research Laboratories, Aberdeen Proving Ground, Maryland, under the direction of Dr. Charles H. Murphy, and by the Space Research Institute of McGill University, Canada, under the direction of Dr. G. V. Bull.

The winds are determined by photographic tracking of chemical trails released by the projectiles during the upper portion of their trajectories. The payload chemical is usually trimethyl aluminum (TMA), which produces a chemiluminescent glow above about 85 km. The glowing chemical trails are distorted by the winds and photographed from ground-based camera sites.

Computer techniques are employed to reduce readings made from the film to obtain profiles of winds versus altitude. Star backgrounds, usually photographed simultaneously with the chemical cloud picture, are used to compute camera azimuths and elevations. Standard programs for computing winds are employed to obtain horizontal winds from smooth trail releases or horizontal and vertical winds from releases which have identifiable features which can be separately tracked.

The purpose of this report is to analyze the irregular horizontal and vertical winds obtained from some of the releases from Yuma (shots Y14 through Y20, in particular) and from Barbados. Dr. N. W. Rosenberg, of the Air Force Cambridge Research Laboratories, has also consented to the use of some of the wind data obtained from Eglin Air Force Base releases conducted under Air Force studies with Georgia Institute of Technology. Analysis of some of these data is also presented here. Wind profiles of the Yuma and Barbados data have been tabulated and reported in previous SIR Technical Reports (1-7) prepared under BRL Contract 169 (Army Contract DA-01-009-MAC-169(X)).

Initially, the purpose of this pilot study was to investigate vertical motions. It was decided to study the series of Yuma releases of 16-19 November 1966 because this sequence appeared to provide the best available combination of releases with: (1) separation times approaching internal atmospheric gravity waves periods through one night, (2) trails of long horizontal extent, or at altitudes at which one would expect turbulent break-up of the trail, (3) releases at comparable times on successive days, and (4) some releases with up and down legs. It had been hoped that once the vertical motions had been determined it would be possible to separate the ambient vertical motions from the vertical motions induced by the buoyancy of the trail itself. It was hoped also that some investigation could be made later regarding the implications for the analysis of horizontal winds which is generally based on the contrary and despite the gravity wave prediction of substantial vertical components in a part of the wave spectrum. An added reason for this choice of shots was the fact that the horizontal winds had already been analyzed for these particular trails (Ref. 6).

However, during the course of the investigation emphasis was shifted to a study of the irregular horizontal winds because the trails did not show the identifiable structure which was to have provided a key feature of the analysis. Therefore, despite the recent development of a single-station analysis technique, not as much could be done with vertical motions as had been hoped originally.

SECTION II

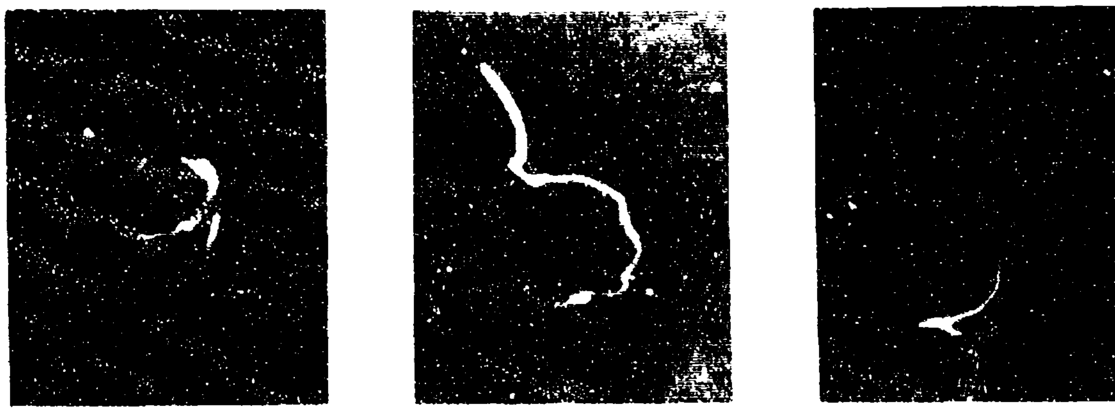
DATA ACQUISITION

Data acquisition techniques and equipment are essentially the same at Barbados and Yuma ranges. Chemical trails (usually trimethyl aluminum--TMA) are released from projectiles fired nearly vertically from the gunsite. The Barbados gun is located at 59.4^{o} west longitude, 13.0^{o} north latitude. The Yuma gun is located at 114.3^{o} west longitude, 32.9^{o} north latitude. Usually, the chemical is released on the up leg of the trajectory of the projectile. However, in some cases it is released on the down leg or on both up and down legs.

The luminous chemical trails are readily visible from ground level. Their glows are caused by a chemiluminescent process above about 85 km at night or by a combination of chemiluminescence, scattered sunlight, and resonance radiation at twilight. Upper atmospheric winds quickly distort the trail from its initial shape. These winds also produce irregular structure on most of the trails, particularly below about 105 km. The trails continue to move with the winds and to diffuse until they fade from view. Typical cloud lifetimes are from 5 to 20 minutes. Usable wind data can be obtained over most of the cloud lifetime by observing successive trail positions by photographic triangulation from ground-based observing sites.

Space Instruments Research (SIR) operates several observing sites at typical distances of 100 to 300 km from the gunsite. Equipment at each site consists of a camera unit containing two 7-inch focal length cameras. The camera unit is mounted on a concrete pedestal and is operated by an electronic control unit that programs exposures of 3, 6, and 12 seconds duration every 30 seconds. Coded time, shot number, and site information are recorded on each frame of film. Each camera unit is powered by an accurately regulated power supply so that pictures can be taken simultaneously at each site. Figure 1 shows some sample photographs of chemical trails. Figures 2 and 3 show the site layouts at Yuma and Barbados and also show typical release locations.

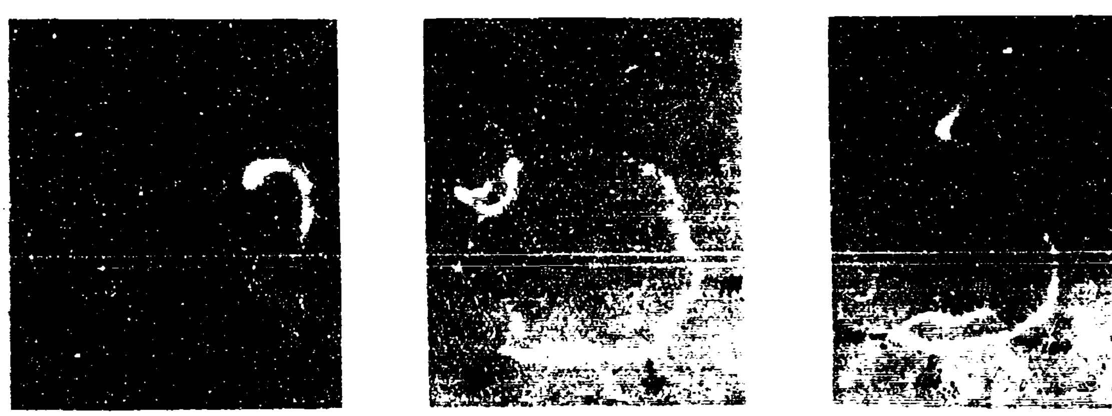
Photographs taken 132 seconds after firing:



YUMA BLYTHE GILA BEND

This set of pictures shows trail just as the vehicle stopped releasing chemical. Numbers indicate altitude in kilometers.

Photographs taken 202 seconds after firing:



YUMA BLYTHE GILA BEND

Figure 1. Photographs of Shot Y26

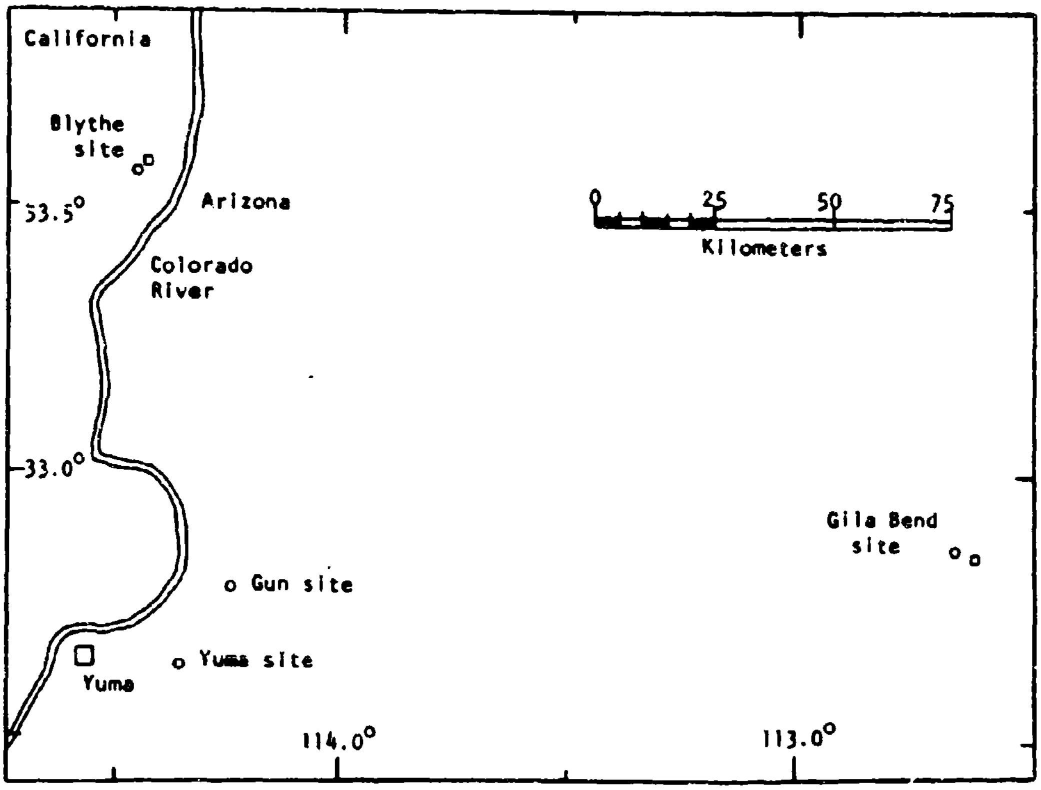


Figure 2. Location of SIR Photographic Stations, HARP, Yuma

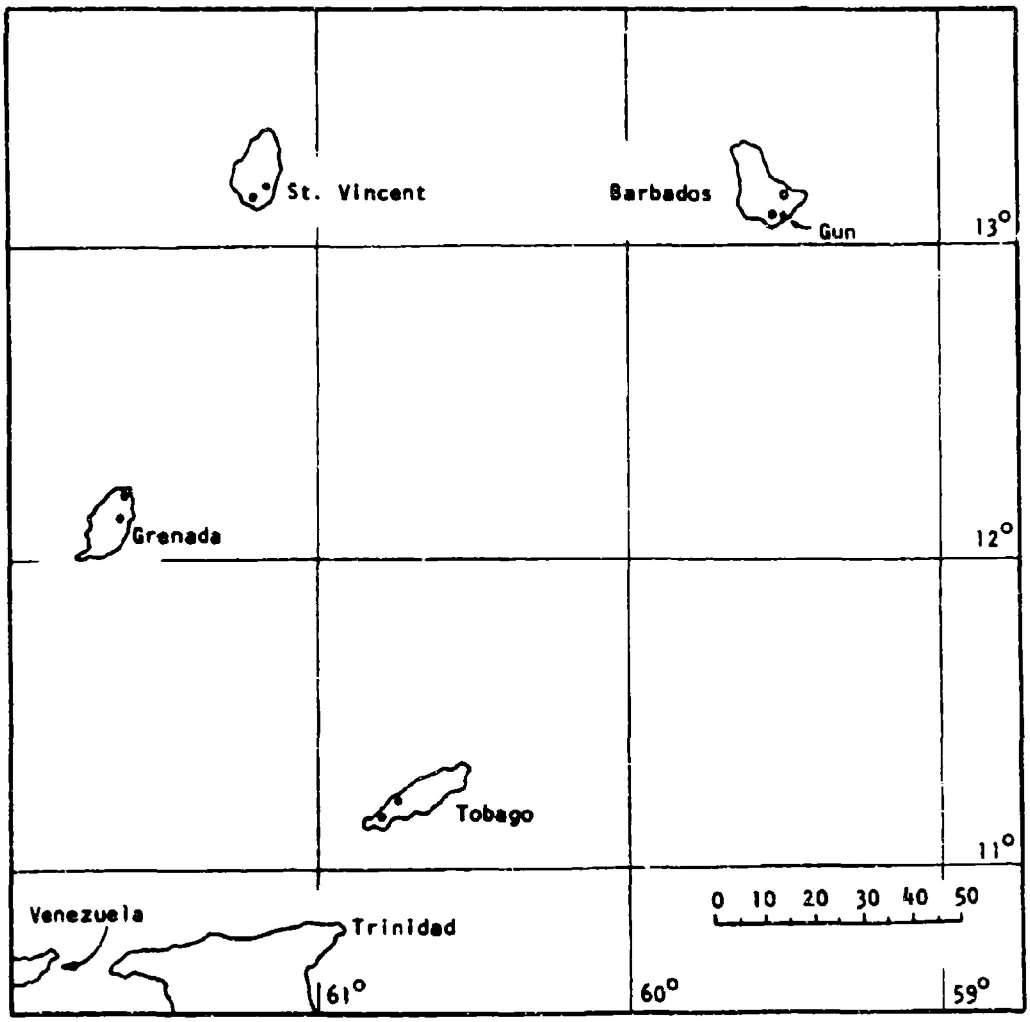


Figure 3 Location of SIR Photographic Stations, H.A.R.P., Barbados

Two stations are located on each of the four islands, as shown. While only one station on each of any two islands is sufficient for determination of winds by triangulation, several stations were found necessary because of prevalent cloud conditions in the area. Accuracy of the data reduction is also increased by use of films from more than two islands.

SECTION III

DATA REDUCTION

The reduction of the film data to obtain winds requires several steps. A preliminary step that is necessary for each new set of observing sites is to take accurate site locations and compute various transformation coefficients for the coordinate systems used in the wind reduction calculations. It is also necessary to compute accurate focal lengths for each camera to be used in the data reduction. Camera focal lengths are calculated by a program that employs measurements of the locations of pairs of star images on the film. Star images on the film are also used in a program that computes the camera azimuth and elevation for each rig setting used during the run. In order to minimize the time-consuming star-reading work, the camera rigs are moved as few times as possible during a single operation.

After these preliminary stages have been performed, there are two basic types of techniques for computing positions of the trails. The point-position technique can be used on trails or portions of trails that have features that can be uniquely identified from two or more observing sites at two or more different times. The trail-position technique is used on trails or portions of trails that are smooth, with no distinguishable features at all, or none that can be uniquely identified from more than one site. The point-position technique yields height and horizontal coordinates of arbitrarily chosen altitudes on the trail. Hence, only horizontal winds can be computed from the trail-position data.

The point-position program thus yields a set of data x_i, y_i, z_i at each of several times t_i for specific identified features on the chemical cloud. The trail position program yields a set of data x_i, y_i at each of several times t_i for arbitrary pre-selected altitude points on the trail (usually the integer kilometer altitude points). Horizontal winds are computed similarly for the point data and for the trail data. If a linear function is fit to the set of data points,

$$x = x_0 + V_x t$$
$$y = y_0 + V_y t \tag{1}$$

then the computed constant coefficients V_x and V_y are the constant components of the horizontal winds. These are called the straight-line winds, if it is necessary to distinguish them from time varying winds determined by fitting parabolic function to the set of data

$$x = x_0 + V_{x0}t + \tfrac{1}{2}a_x t^2$$
$$y = y_0 + V_{y0}t + \tfrac{1}{2}a_y t^2 \tag{2}$$

The so called parabolic winds, given by

$$V_x = V_{x0} + a_x t$$
$$V_y = V_{y0} + a_y t \tag{3}$$

vary linearly over the lifetime of the cloud. Ordinarily, only straight-line winds are computed. However, in order to study irregular winds and wind variations, some results of parabolic winds computations are reported here.

Vertical winds are computed from point position data in the manner of equation (1)

$$z = z_0 + V_z t \tag{4}$$

where V_z is the vertical wind.

Both the point-position and trail-position techniques have been used regularly for determining horizontal winds (and vertical winds in the case of the point-position technique). Recently a new wind-computing technique has been developed called the single-site technique. This procedure requires that the location of a cloud feature be known at some initial time and that the feature can be tracked from time to time from a single observing site. But the single-site technique relaxes the requirement of the point-position technique that a feature must be uniquely identifiable from two or more sites at each time. The single-site technique determines the wind by calculating the linear, constant-velocity motion in space which (starting from the known initial position) would most nearly reproduce the observed film positions at the observation times. A more detailed explanation of the single-site technique is given in Appendix A. In principle, the single-site technique can be used to compute vertical winds as well as horizontal winds, although its ability to do so accurately had yet to be investigated prior to this study. In view of the great interest in vertical winds in connection with this study, it was decided that a trial study would be done to determine the efficiency with which the single-site technique could be used to compute vertical winds. Potentially, this technique with its less strenuous requirements on the input data might yield more vertical wind information than the standard point-position data.

SECTION IV

RESULTS

Since most of this report deals with data obtained from the series fired on the nights of 16 through 19 November 1966 from Yuma, a table summarizing firing times and altitudes covered by the various shots is given in Table I. The shots will be referred to in this report by the trail number designation given in the left hand column of Table I. In addition, some detailed data from shot B31, fired from Barbados on 17 November 1965 at 18:15 AST, will also be discussed, as will some data from the Air Force release code named Sara, fired on 17 May 1963 at 19:06 CST from Eglin AFB, Florida.

1. VERTICAL WINDS

   a. Point-Position Results. Figure 4 shows the results of point-position values of altitude versus time on several points observed on trail Y17. As can be seen from inspection of this figure, there is a consistent trend in the vertical motion of the points. Figure 5 shows the computed vertical winds and probable errors. The dashed curve through these data is a subjective estimate of the vertical wind profile variation with altitude for this trail. The vertical winds and probable errors for shot Y17 and others are given in tabular form in Table II. These tables show that the vertical winds observed for shot Y17 were of generally larger amplitude. The Y17 data also exhibit the most significant consistency of variation of vertical wind with altitude. All of the data in Table II were computed by the straight-line-fit process to position data determined by the point-position results. The probable errors are the computed probable errors in the slope of the line fit to the data.

   b. Single-Site Results. It is quite difficult to obtain vertical winds by the point position method, but until now this was the only available method which could be used. The primary difficulty in the application of the point position method is that it

TABLE I

TABLE OF TRAIL INFORMATION
FROM YUMA, NOVEMBER 1966 SERIES

Trail No.	Shot No.	Date	Time (MST)	Altitudes (km)
Y10	0017	16 November 1966	18:41:24	92-112
Y11	0018	16 November 1966	20:41:52	90-119
Y12	0019	16 November 1966	22:32:07	90-112
Y13	0020	17 November 1966	00:16:13	96-120
Y14	0022	18 November 1966	18:18:47	88-120
Y15	0023	18 November 1966	20:12:21	85-127
Y16	0024	18 November 1966	21:49:42	89-139
Y17	0025	18 November 1966	23:43:09	89-138
Y18	0026	19 November 1966	01:01:22	91-144
Y19	0027	19 November 1966	02:35:35	88-120
Y20	0028	19 November 1966	04:52:53	92-167
Y21	0030	19 November 1966	19:45:00	93-142
Y22	0031	19 November 1966	21:21:29	91-111
Y23	0032	19 November 1966	22:37:53	90-111
Y24	0033	19 November 1966	23:59:14	91-147

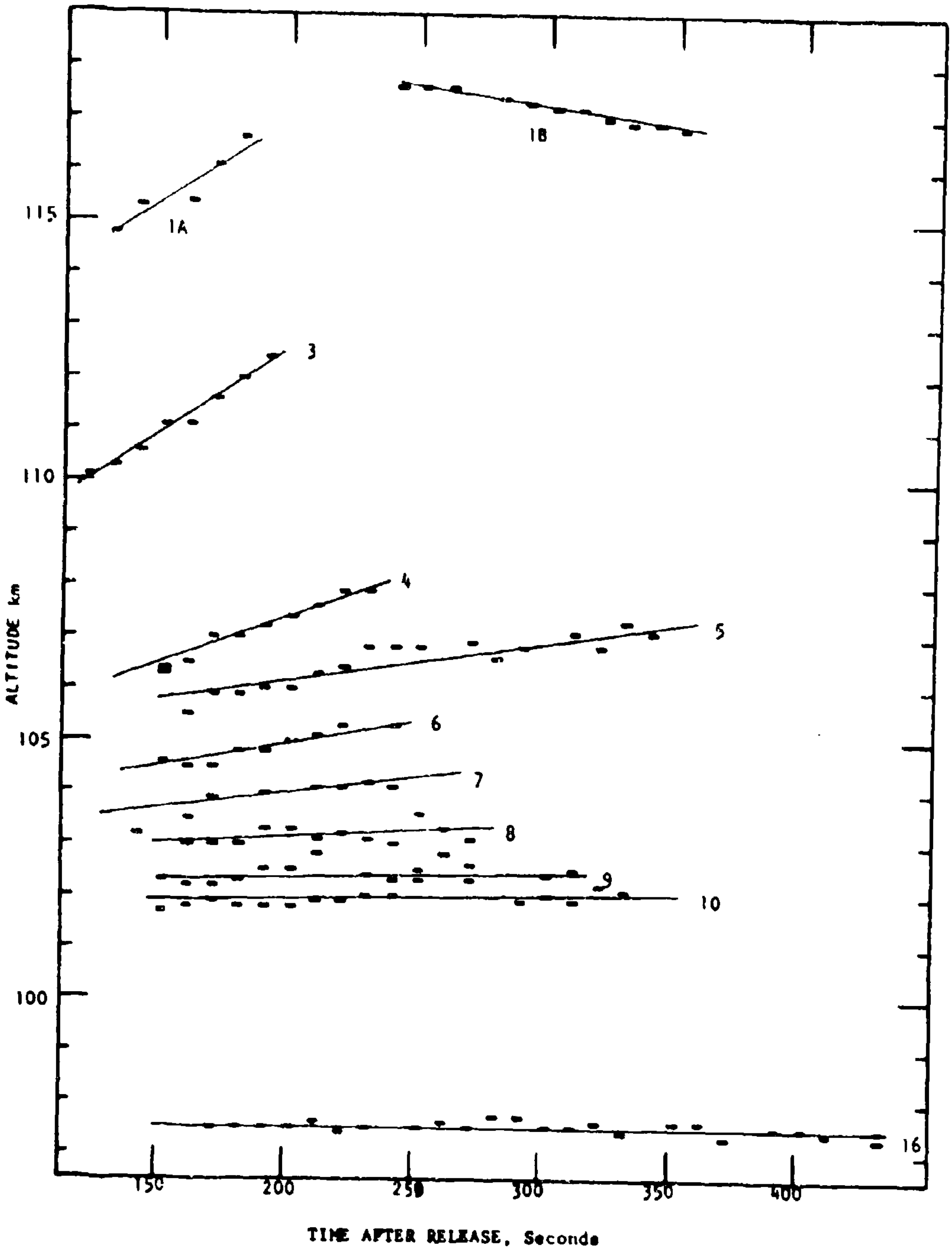


Fig. 4. Height versus Time for Some Points on Trail Y17

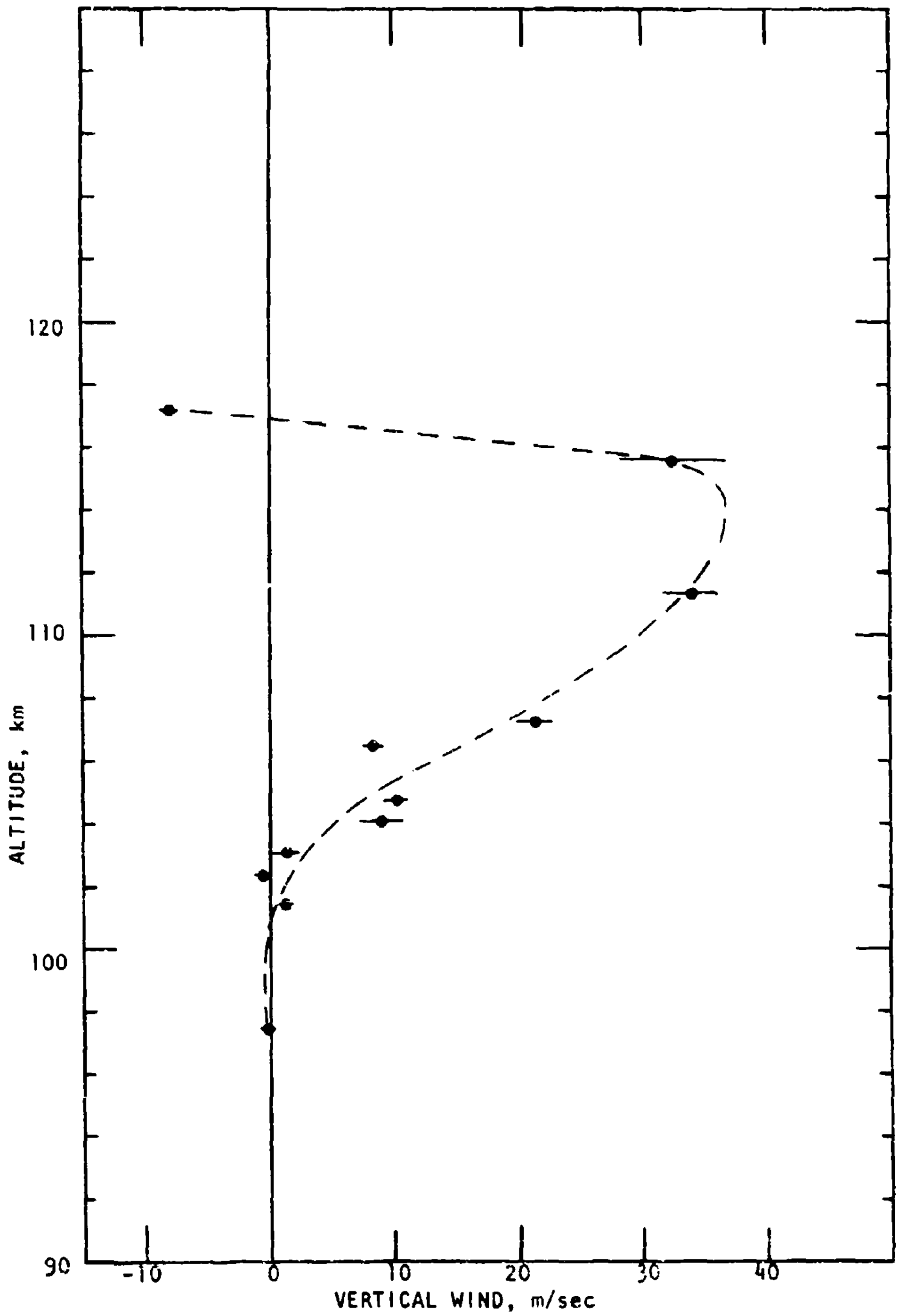


Fig. 5. Computed Vertical Winds for Trail Y17

TABLE II

VERTICAL WINDS COMPUTED BY THE POINT-POSITION METHOD. ALTITUDES GIVEN ARE THE MEAN ALTITUDES OR THE INTERVAL OF OBSERVATION

Shot Y15

Height (km)	Vertical Wind (m/sec)	
95.1	-1.0	±0.5
100.5	1.1	±1.5
102.7	0.5	±0.3
104.9	-0.5	±0.3
110.1	1.5	±0.8
121.0	14.6	±0.4

Shot Y16

Height (km)	Vertical Wind (m/sec)	
92.0	7.2	±0.3
100.0	1.2	±0.6
102.8	-1.0	±1.1
104.6	-1.0	±0.2
112.2	24.7	±0.9
128.1	3.3	±1.9
139.1	-5.2	±3.3

Shot Y19

Height (km)	Vertical Wind (m/sec)	
86.7	-17.8	±2.7
94.3	- 0.8	±7.1
98.9	16.3	±2.2
117.5	16.1	±2.4

Shot Y17

Height (km)	Vertical Wind (m/sec)	
97.5	-0.1	±0.2
101.9	1.5	±0.7
102.4	-0.6	±0.8
103.1	1.4	±1.2
104.1	9.1	±1.9
104.8	10.3	±1.1
106.5	8.2	±0.8
107.3	21.3	±1.7
111.3	33.8	±2.3
115.6	32.4	±4.6
117.2	-8.1	±0.4

Shot B31

Height (km)	Vertical Wind (m/sec)	
93.8	6.9	±1.4
95.6	-8.5	±1.2
96.0	-1.0	±2.0
99.4	6.5	±0.9
99.4	5.8	±0.7
102.2	6.5	±1.1
104.6	0.8	±1.7
110.9	10.1	±1.6
111.5	-10.3	±2.5
117.7	31.3	±2.0

Table II - continued

TABLE II
(Concluded)

Shot Sara

Height (km)	Vertical Wind (m/sec)	
85.9	1.5	±3.0
91.3	-1.2	±0.6
95.6	-0.1	±0.3
99.5	0.1	±0.6
101.0	1.5	±0.6
102.2	1.4	±2.7
104.9	4.7	±0.6
105.0	0.9	±0.3
105.1	10.6	±0.4
108.6	1.8	±0.2
109.1	-0.9	±0.2
114.8	3.2	±0.4
119.9	-1.9	±0.3
134.0	25.0	±9.7

requires that a cloud feature be identified not only on several successive frames of film from a site but also be simultaneously identified at the corresponding times on the film from another site. hus, this method cannot be employed on smooth, featureless sections of trails. Frequently, however, in the turbulent region below about 105 km, although a feature can be tracked from frame to frame on the film from a site, the cloud is so irregular in appearance that the location of the same feature on the film from another site is impossible. Hence, it was thought that the new single-site technique, mentioned in Section III, might prove useful as a tool for the measurement of vertical winds.

In order to determine the accuracy of the single-site technique, it was used on some of the cloud film data that were also used in the calculations of the Sara vertical winds by the point-position method. These results indicate that a feature must be seen for at least seven times from a single site in order for reasonably accurate results to be obtained by the single-site method. The computed vertical winds from points observed seven or more times were compared to the vertical winds previously computed by the point-position method. The rms deviation between the two results was over 6 m/sec, whereas the point position vertical winds had computed probable errors of less than 3 m/sec, rms. More than 70 percent of the point-position vertical winds had computed probable errors of less than 1 m/sec while only 28 percent of the single-site results differed from the point position results by less than 1 m/sec. It appears, therefore, that the single-site technique will not produce sufficiently reliable results that it can be widely used for vertical wind computations. However, in those cases when cloud points can be tracked for many times from a single site but the corresponding points cannot be identified from another site, the single-site technique does offer a reasonably accurate method of determining vertical winds.

c. Vertical Propagation of Winds. To investigate possible interactions of the vertical winds and the horizontal winds, two possible manners in which vertical winds might behave were explored. The first question to be investigated was whether or not the cloud points as they move up or down tend to alter their horizontal motion so as to adjust to the mean wind profile. Figures 6 and 7 show the profiles of the northward and eastward components of the mean wind determined from the cloud Sara. The point-position data were subjected to a least squares linear fit of the altitude versus time as in equation (4), thus yielding a constant vertical wind. A parabolic fit to the horizontal point coordinates was calculated by equation (3). Figures 6 and 7 show arrows representing the variation of the horizontal wind components of the cloud points as these points vary in altitude. The tail of each arrow is located at the initial altitude and wind value observed for a particular point, and the tip of the arrow is located at the final altitude and wind value for that point. If cloud points moved in a vertical direction in such a manner as to alter the horizontal velocities to adjust to the mean wind profile, then the arrows in Figures 6 and 7 would lie parallel to or be superimposed on the wind-profile curves shown in these figures. However, this behavior is not observed, and it must be concluded that vertical motion does not occur in this manner.

It has previously been determined that detectable variations in the horizontal winds occur over the lifetime of long duration trails (Rosenberg and Justus (8)). These observed variations can be described as a vertical shifting of sections of the horizontal wind profile with some modification of the profile occurring with the vertical shift. A second possibility for the manner in which vertical motions of cloud points take place is that the cloud points follow the vertical motions of the changing horizontal winds determined, say, by observing height variations of the altitude at which constant speed values occur. The trail

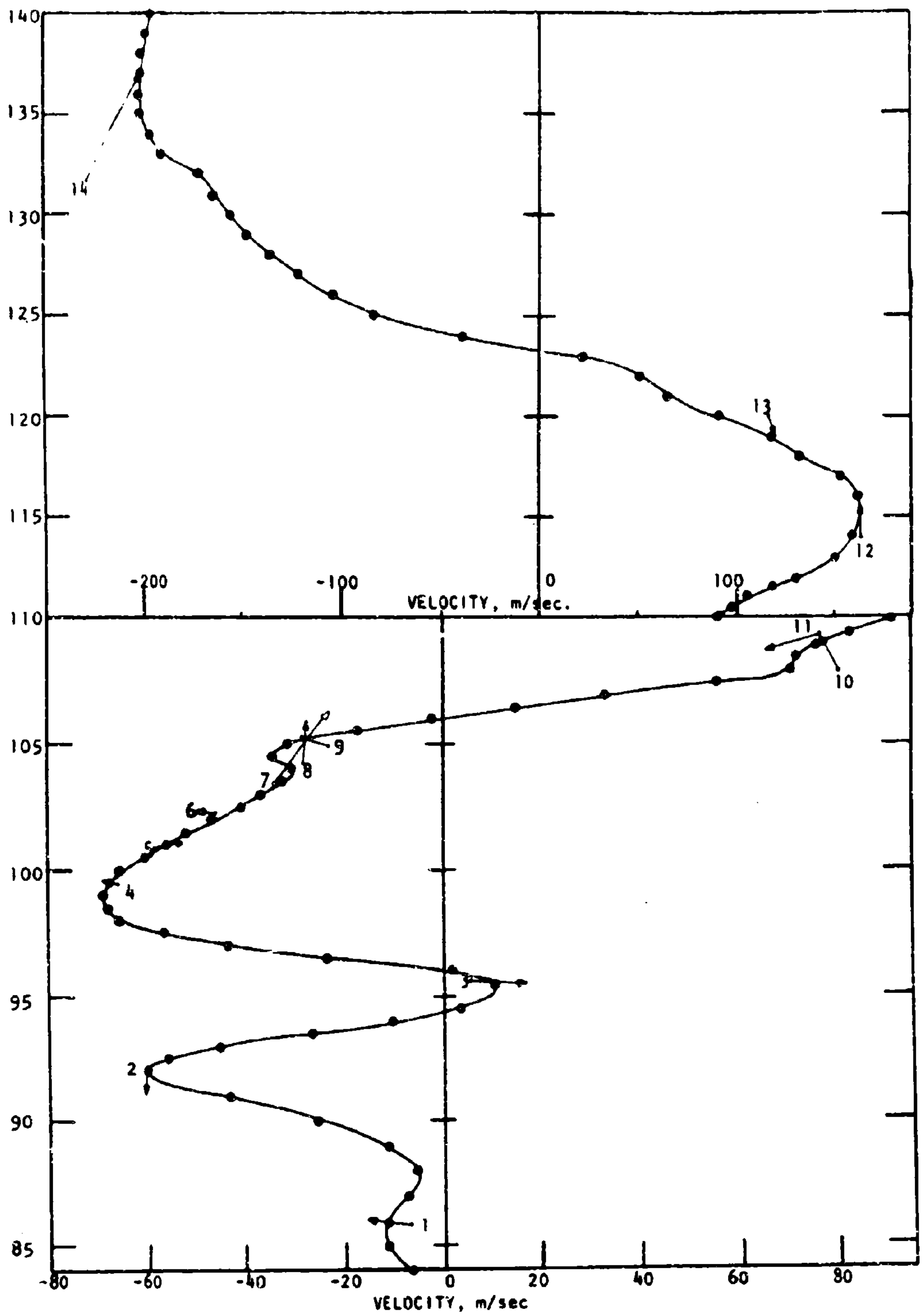


Fig. 6. Profile of Northward Mean Winds for Trail Sara, with Velocity Variations of Several Points Shown as the Arrows.

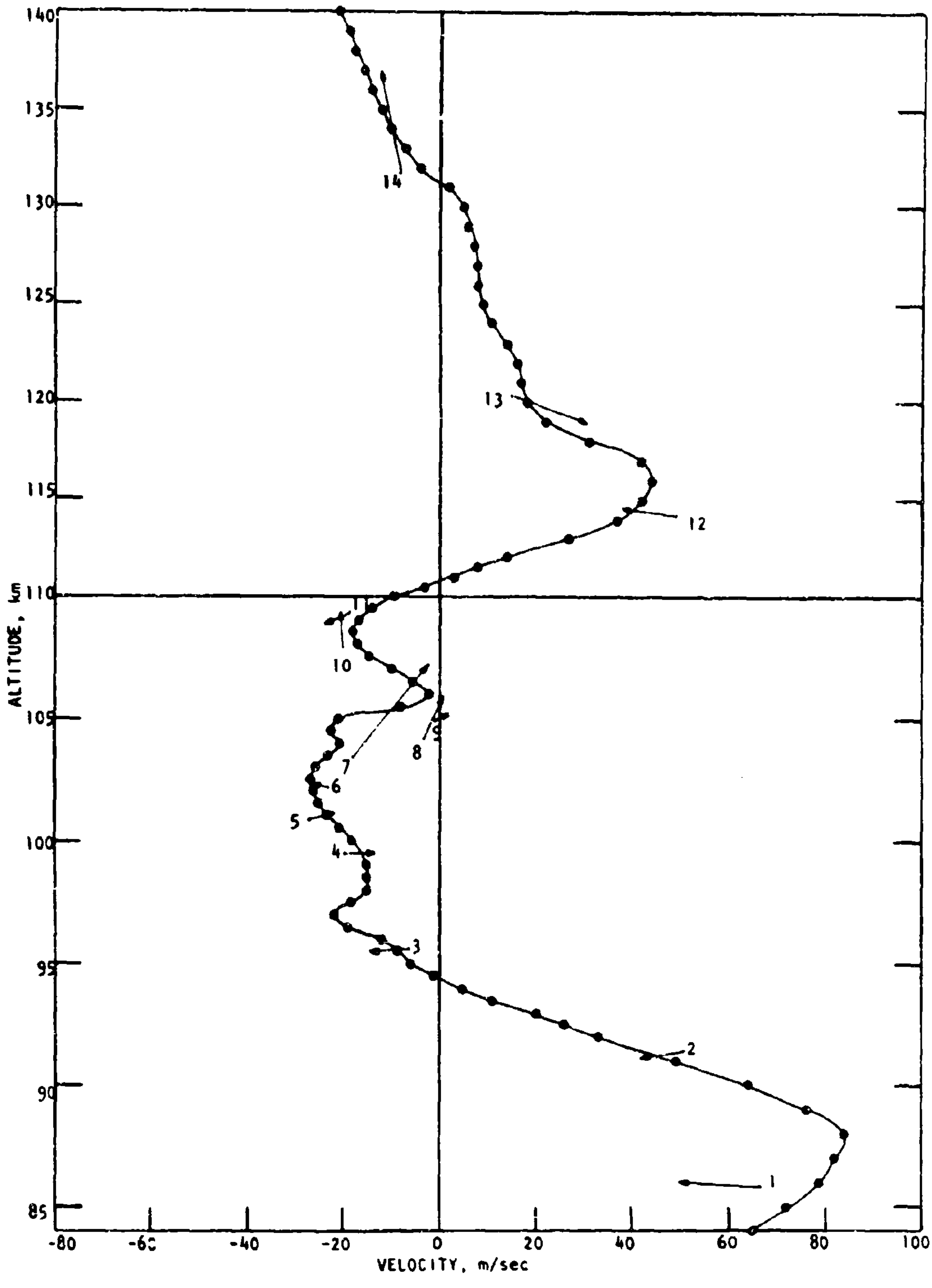


Fig. 7. Profile of Eastward Mean Winds for Trail Sara, with Velocity Variations of Several Points Shown as the Arrows.

position data for the trail centerline coordinates of two trails (B31 and Sara) were subjected to parabolic least squares analysis, yielding a set of linearly varying horizontal winds at each altitude on the trails. Figures 8 and 9 show the results obtained by evaluating the horizontal winds at a sequence of times (times of evaluation are indicated as the heavy vertical lines). Figures 8 and 9 show the variation with time of the altitudes at which constant wind speed values occurred. The wind speed values are indicated for various curves shown in these figures. Significant vertical motion of these constant speed points can be seen in these figures. Also shown in Figures 8 and 9 are the altitude versus time variations determined from point position tracking of several cloud points. A substantial, though not complete, correlation is seen to exist between the vertical motions of the cloud features and the constant speed points on the horizontal wind profiles.

Another type of vertical propagation of horizontal wind profiles is observed by comparing successive wind profiles from series of releases that occur throughout a single night (Rosenberg and Edwards (9), Murphy and Bull (10)). This motion seems to be almost a factor of ten smaller than the vertical motion of cloud points, however. Figures 10, 11, and 12 show the variation with time of constant speed points for the three series of releases Y10-Y13, Y14-Y20, and Y21-Y24. The average vertical propagation rate seems to be equal for the speed and for both northward and eastward velocity components. This value was found to be -0.48 ± 0.05 m/sec for the three series illustrated. Extreme values of vertical propagation through the night were found to be about -3 m/sec. These numbers should be compared with observed vertical motion of cloud points given in Table II and with the average vertical propagation rate of the wind profiles over short time intervals of about -1 ± 0.4 m/sec obtained from the data of Figures 8 and 9.

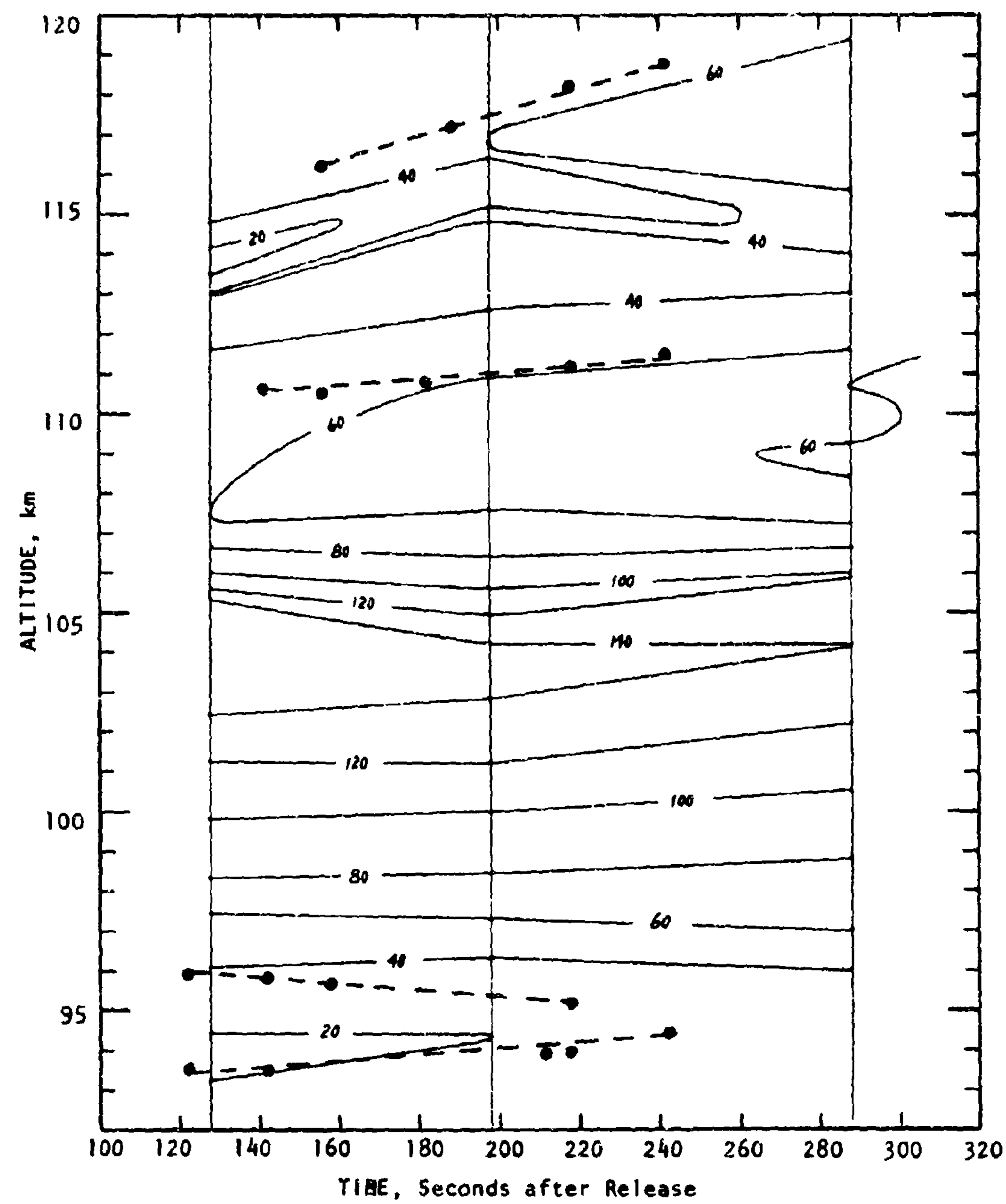


Fig. 8. Altitude Variation of Constant Speed Points on Trail B31. The Altitude Variation of Some Trail Points is Shown as the Dashed Lines. Numbers on the Curve Indicate Constant Values of Velocities in m/sec.

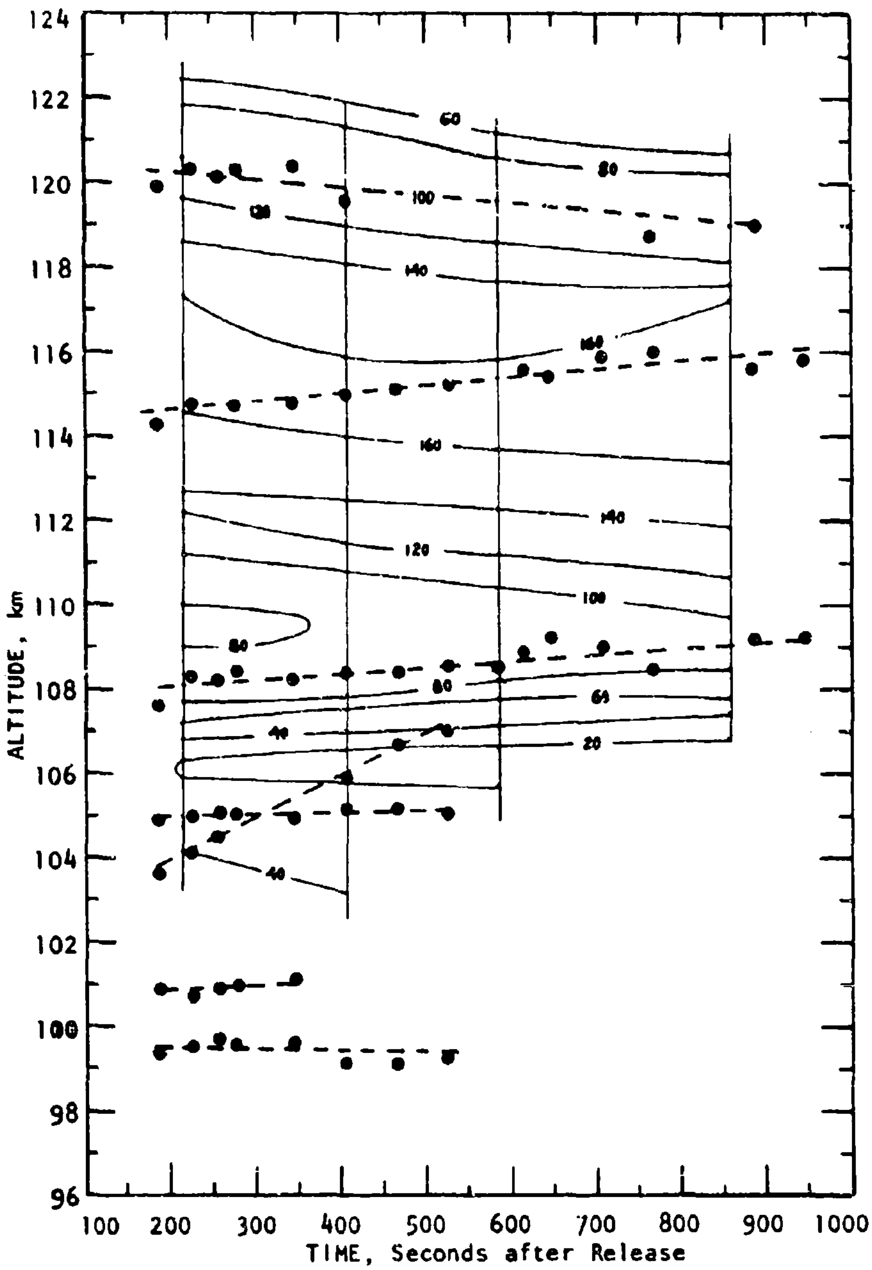


Fig. 9. Altitude Variation of Constant Speed Points on Trail Sara. The altitude variation of some trail points are shown as the dashed lines. Numbers on the curve indicate values of velocities in m/sec.

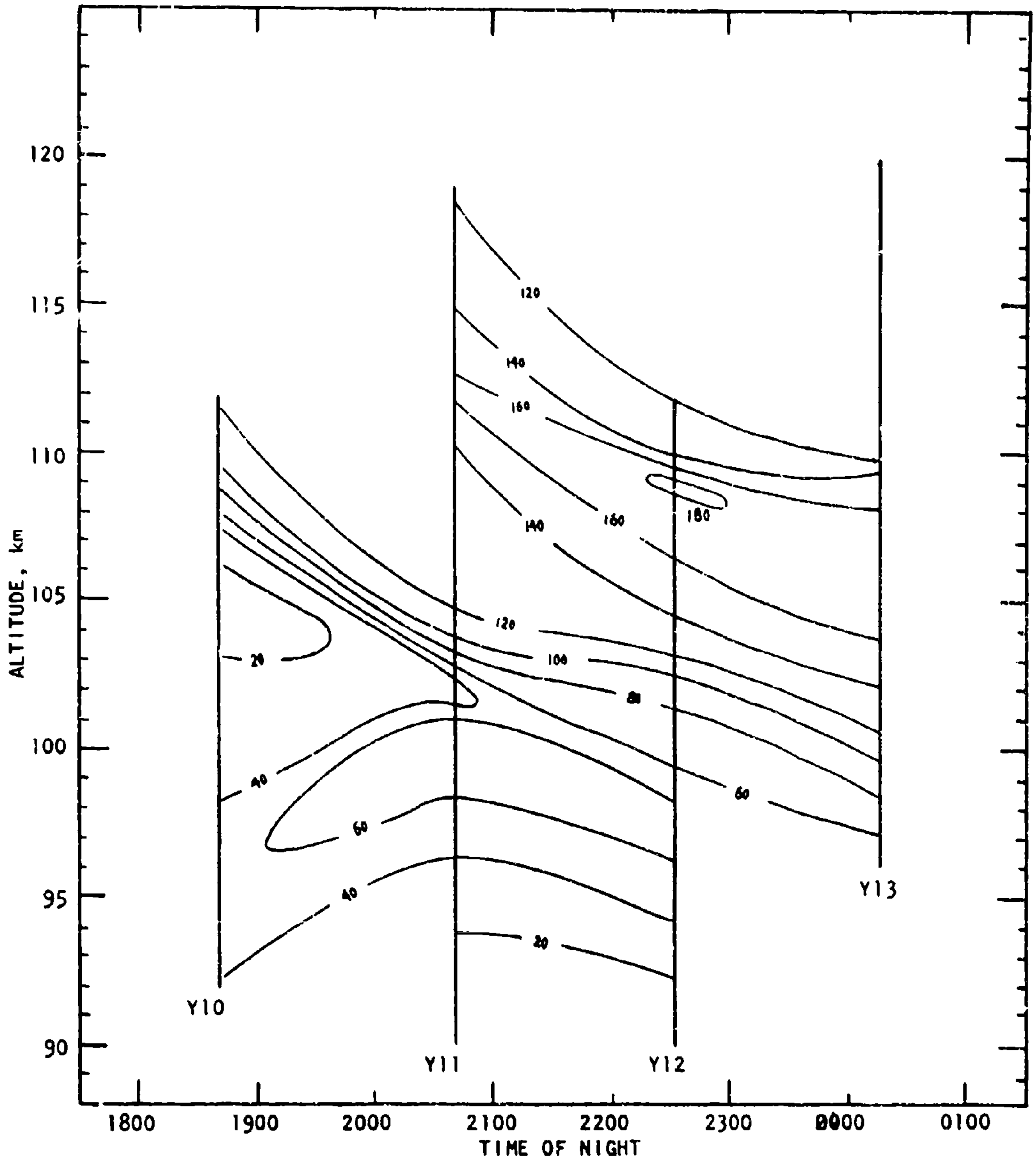


Figure 10. Altitude Variation of Constant Speed Points Throughout the Night of 16-17 November 1966. Numbers on the curves indicate values of speed in m/sec.

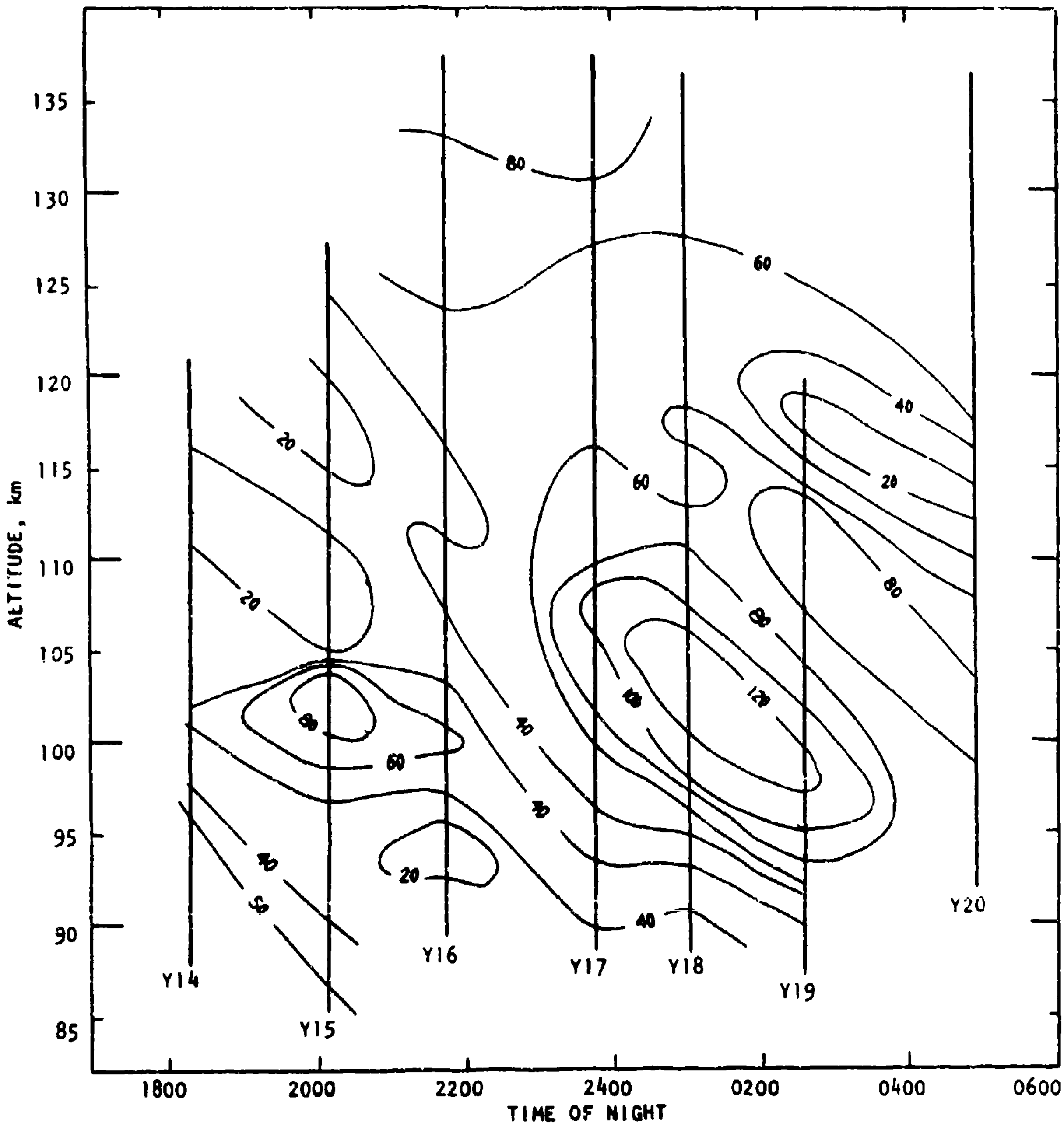


Figure 11. Altitude Variation of Constant Speed Points Throughout the Night of 18-19 November 1966. Numbers on curves indicate values of speed in m/sec.

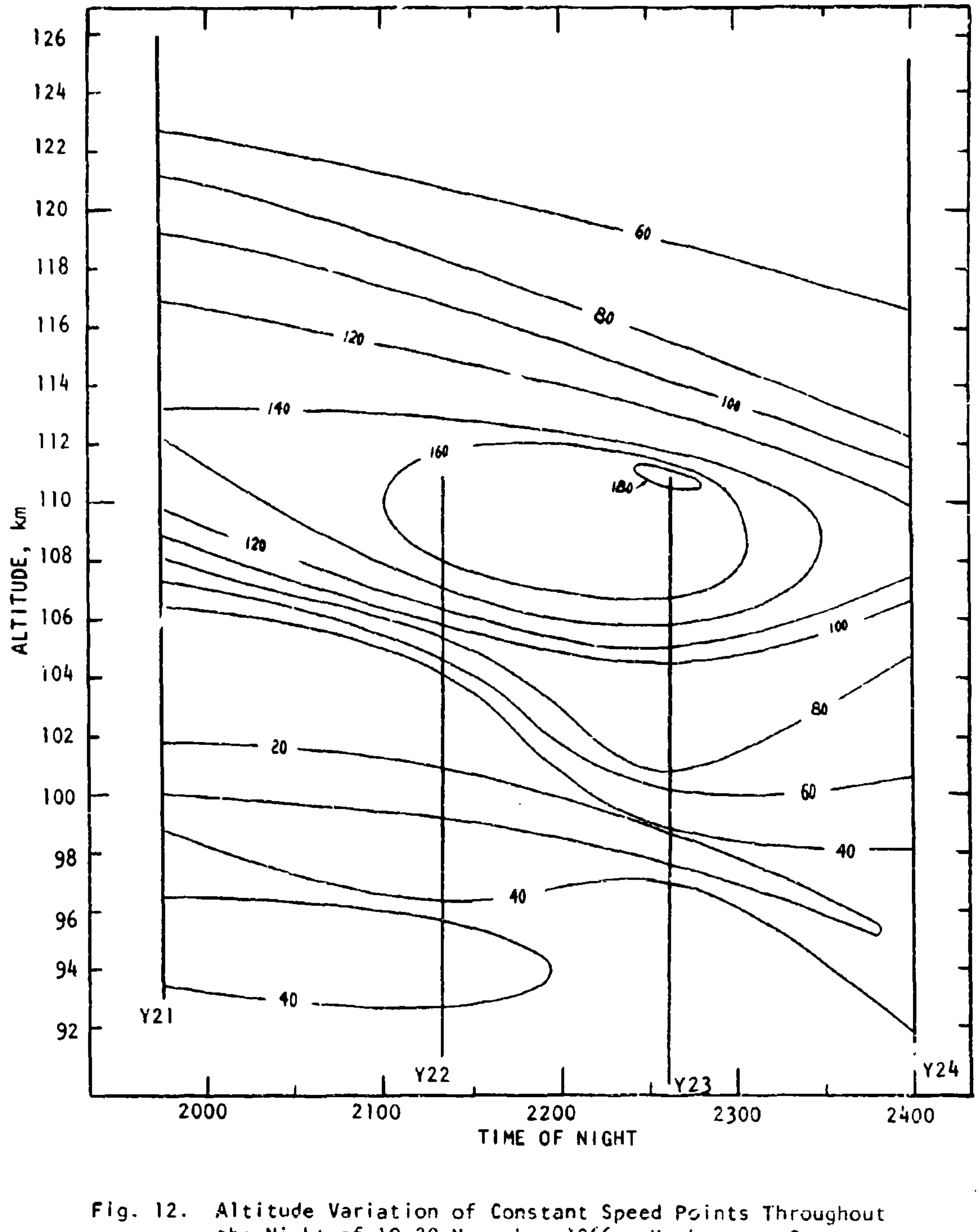


Fig. 12. Altitude Variation of Constant Speed Points Throughout the Night of 19-20 November 1966. Numbers on Curves Indicate Speed in m/sec.

2. IRREGULAR HORIZONTAL WINDS

a. Evaluation of Tidal Winds. In addition to a large irregular wind component, the winds at chemical release altitudes are composed of regular winds such as diurnal, semidiurnal, and other tidal components, mean winds, and possibly long-period winds such as planetary waves. At the present time there is no method of resolving the winds determined from a single chemical release into these various components. However, a series of wind profiles determined at a sequence of closely spaced times can be used to resolve the various wind components. The 15 wind profiles in the Y10 through Y24 series, covering the 16 through 19 November 1966 period, were used in such an analysis. The sequence of northward and eastward component wind values at a given altitude were fit by a least squares process with the function

$$V(t) = A_0 + A_8 \sin\left(\frac{2\pi t}{8} + \phi_8\right) + A_{12} \sin\left(\frac{2\pi t}{12} + \phi_{12}\right)$$
$$A_{24} \sin\left(\frac{2\pi t}{24} + \phi_{24}\right) \qquad (5)$$

where the time t is measured in hours, A_0 is the mean wind, A_8, A_{12}, and A_{24} are the amplitudes of the 8 hour, 12 hour, and 24 hour period tides, and ϕ_8 and ϕ_{12} and ϕ_{24} are phase angles for those tidal components. The A's and ϕ's are the parameters determined by the least squares process. Computed values of the amplitudes and phases are given in tabular form in Appendix B.

The computed tidal parameters were evaluated at each kilometer altitude point and were found to form a smooth profile of variation with altitude. Some of the results are plotted in the following graphs. Figure 13 shows the computed mean wind northward and eastward components (the A_0 values) versus altitude. Wavelike variation of the mean winds similar to that previously observed by Woodrum and Justus (11) is seen in this graph. The vertical wavelength of the mean wind variation is about 22 ± 1 km. Figure 14 shows plots of the 12 and 8 hour period tidal

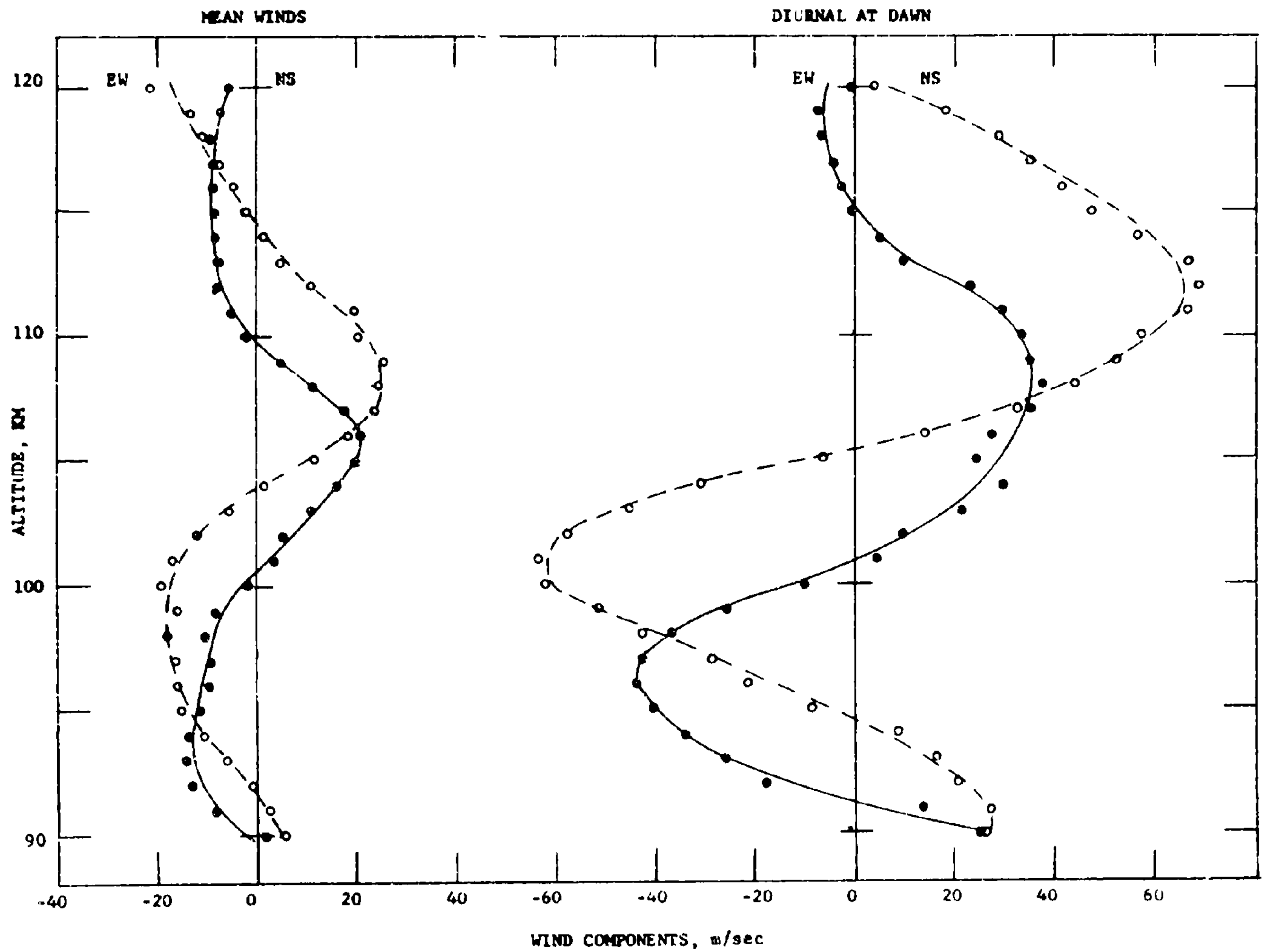


Figure 13. Mean Winds and Diurnal Tide at Dawn
Computed from the Y10-Y24 Series

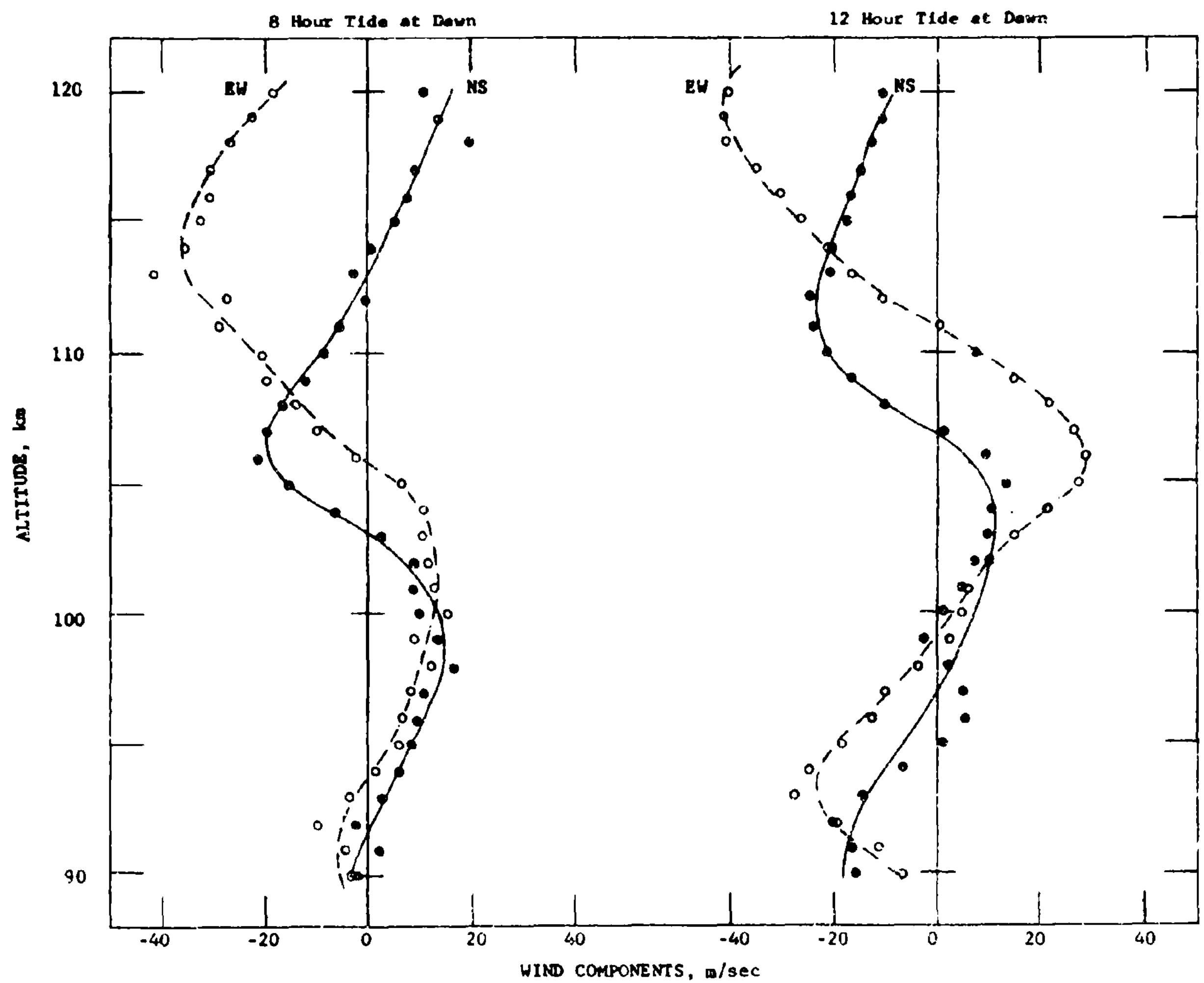


Figure 14. The 8-Hour and 12-Hour Period Tides at Dawn as Computed from Y10-Y24 Series

component evaluated at dawn. Figures 15 and 16 show the computed amplitudes of the various tidal components and the speed of the mean wind. Figure 15 also shows theoretical values of the diurnal tide computed by Lindzen (12). The agreement is quite good when allowance is made for the fact that dissipative action, which is known to occur at these altitudes, was neglected in the theoretical computations. Because this study is concerned primarily with the irregular winds, no detailed analysis of the tidal wind results will be given.

b. Evaluation of the Irregular Horizontal Winds. After the mean winds and tidal components have been determined from a series of releases such as the Y10 through Y24 sequence, then these values may be subtracted from the observed winds to yield a residual wind component. These residual winds can be evaluated at each altitude for each of the profiles in the sequence. Profiles of these residual winds for releases Y14 through Y20 (18-19 November 1966) are shown in Figures 17 through 23. Tabulated values are also given in Table III. The rms values of these residual winds obtained from the Y10 through Y24 series are shown in Figure 24. The magnitude and variation of these residual winds is similar to that of the irregular winds previously determined by Woodrum and Justus (13). Hence, the residual winds computed here will be considered to be the true irregular horizontal wind components. However, it should be noted that a least squares determination of seven parameters (the A's and ϕ's in equation (5)) from at most 15 data points (the sequence of wind values from Y10 through Y24 at a given altitude) is subject to the possibility of considerable error, especially when the irregular component has so large an amplitude compared to the regular tidal wind amplitudes. The same tidal calculations and evaluation of residual winds was done on the sequence of releases B31 through B42 (17-23 November 1965). It is encouraging to note that the rms residual winds obtained from this series, and shown in Figure 25, are so similar to

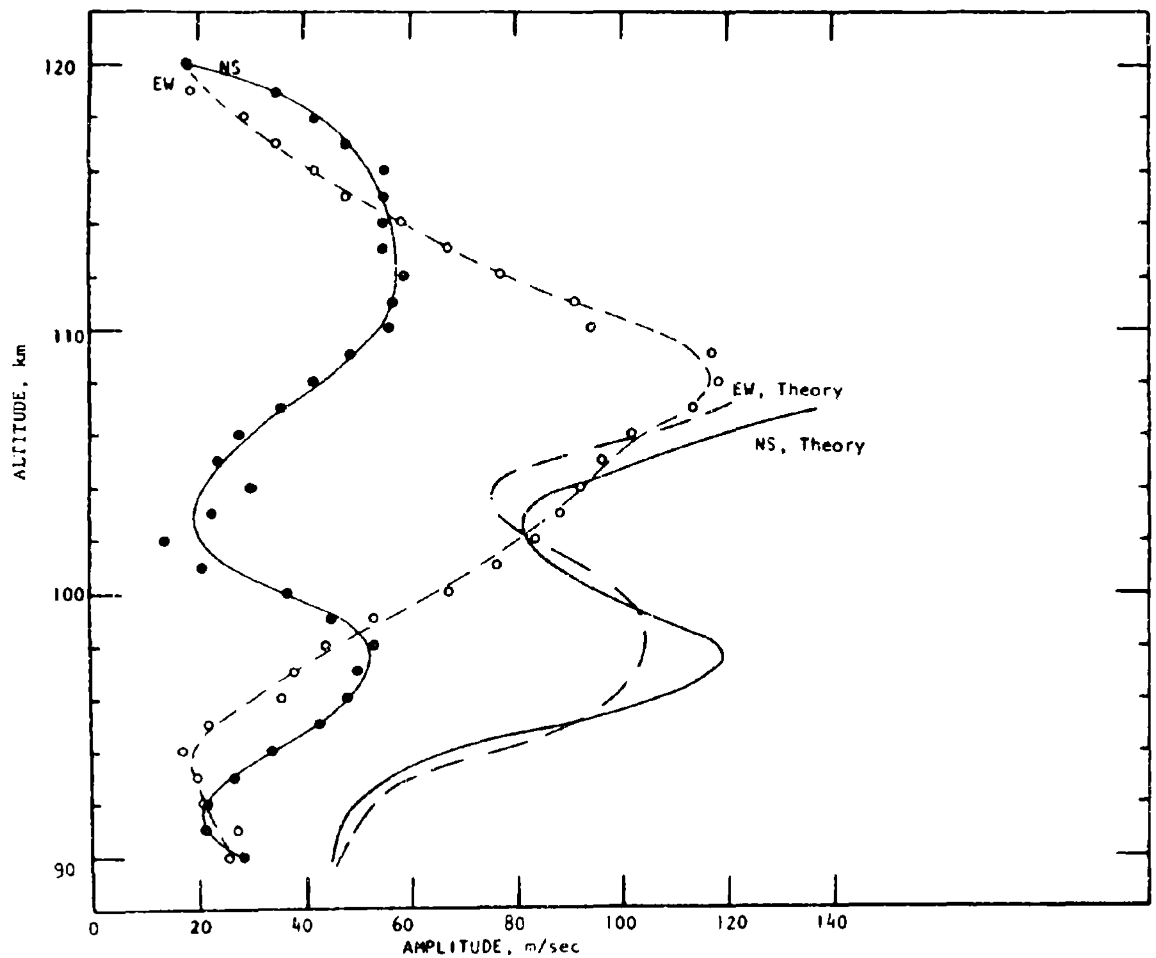


Figure 15. Observed Amplitude of the Diurnal Tide Compared to the Theoretical Predictions of Lindzen.

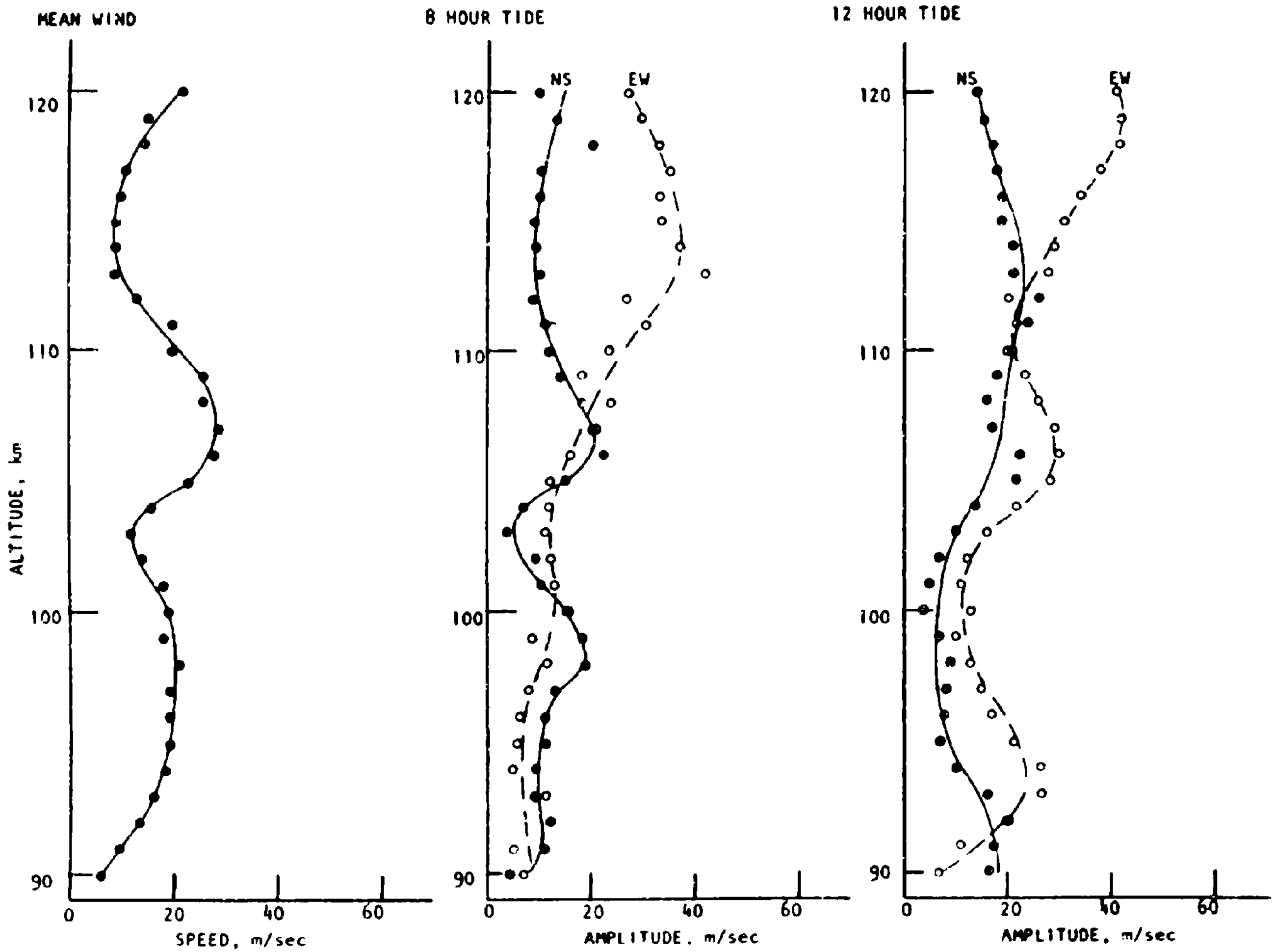


Figure 16. Speed of the Mean Wind and the Amplitudes of the 8 Hour and 12 Hour Period Tides Computed from the Y10-Y24 Series.

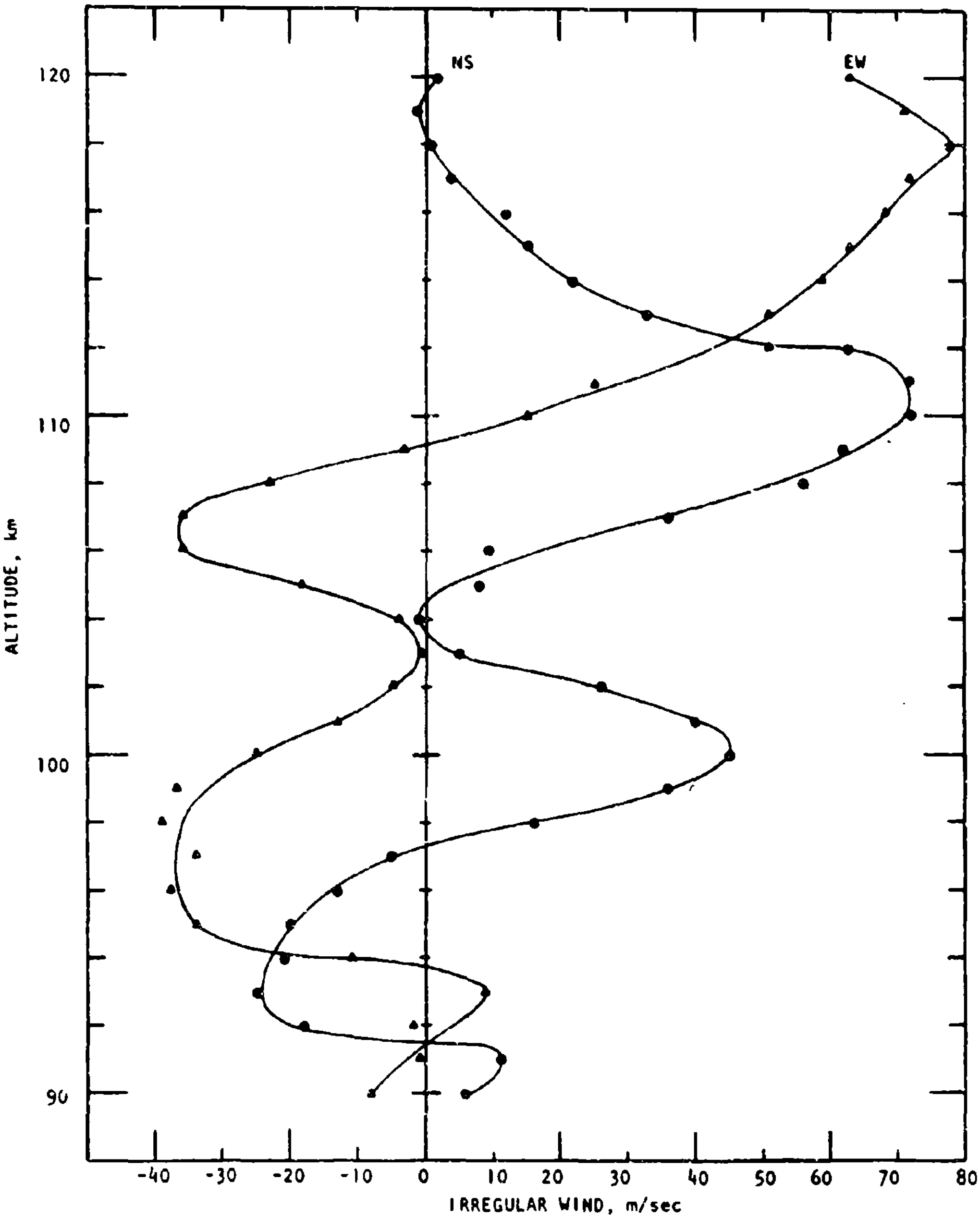


Figure 17. The Y14 Irregular Winds

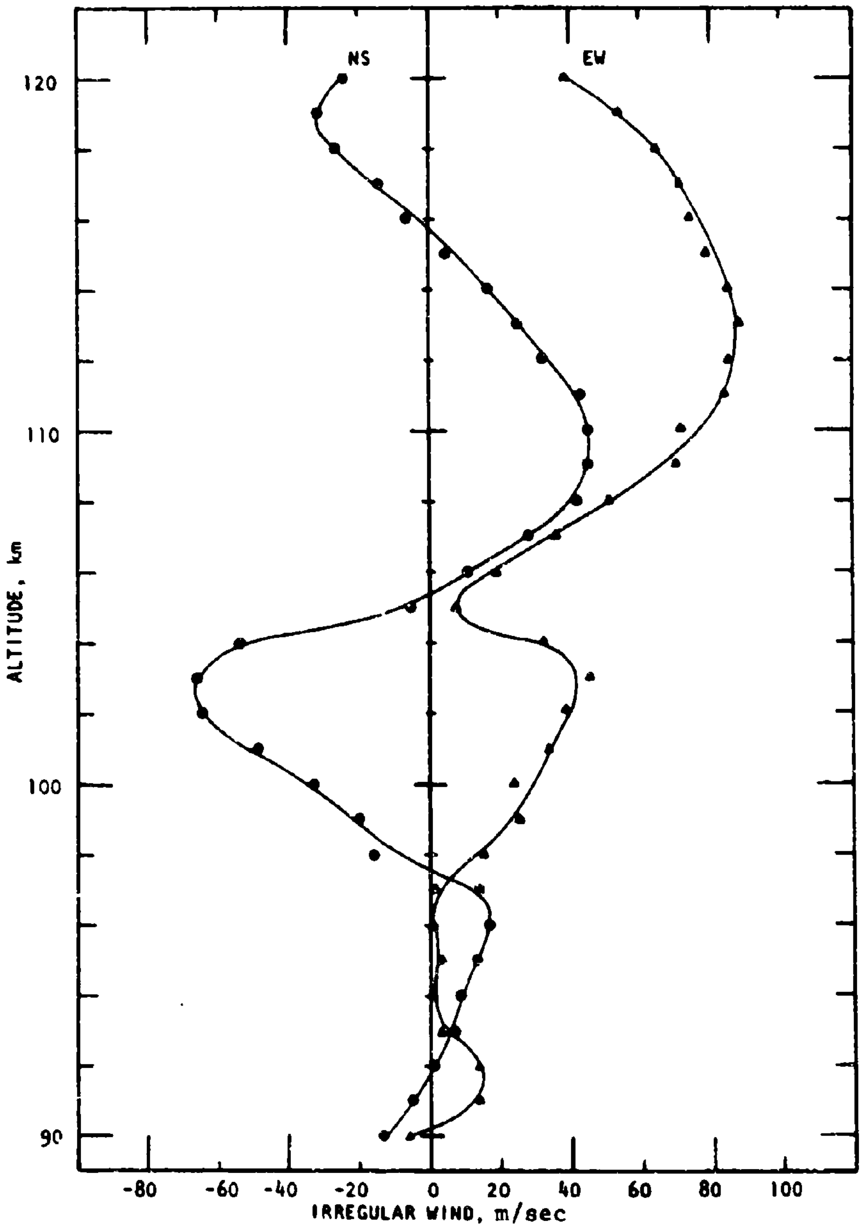


Figure 18. The Y15 Irregular Winds

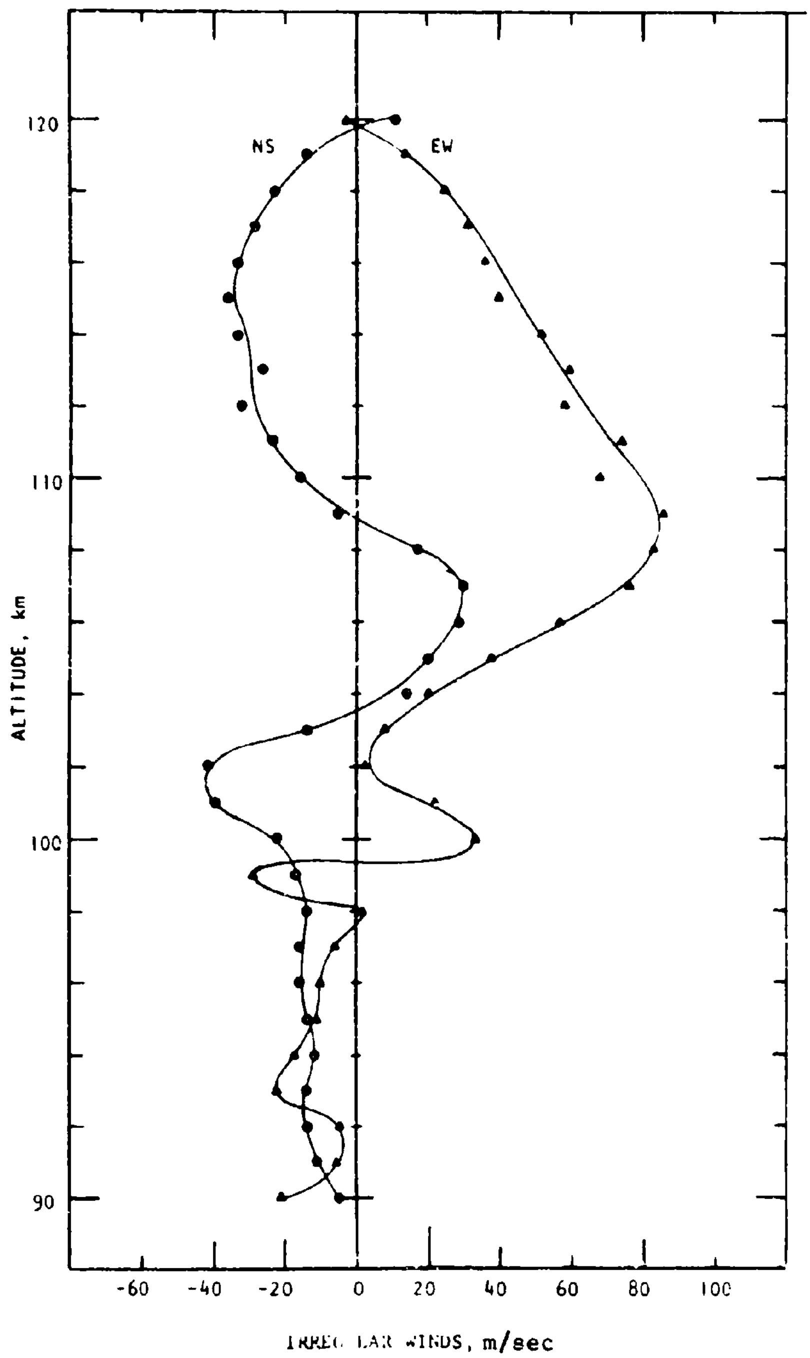


Figure 19. The Y16 Irregular Winds

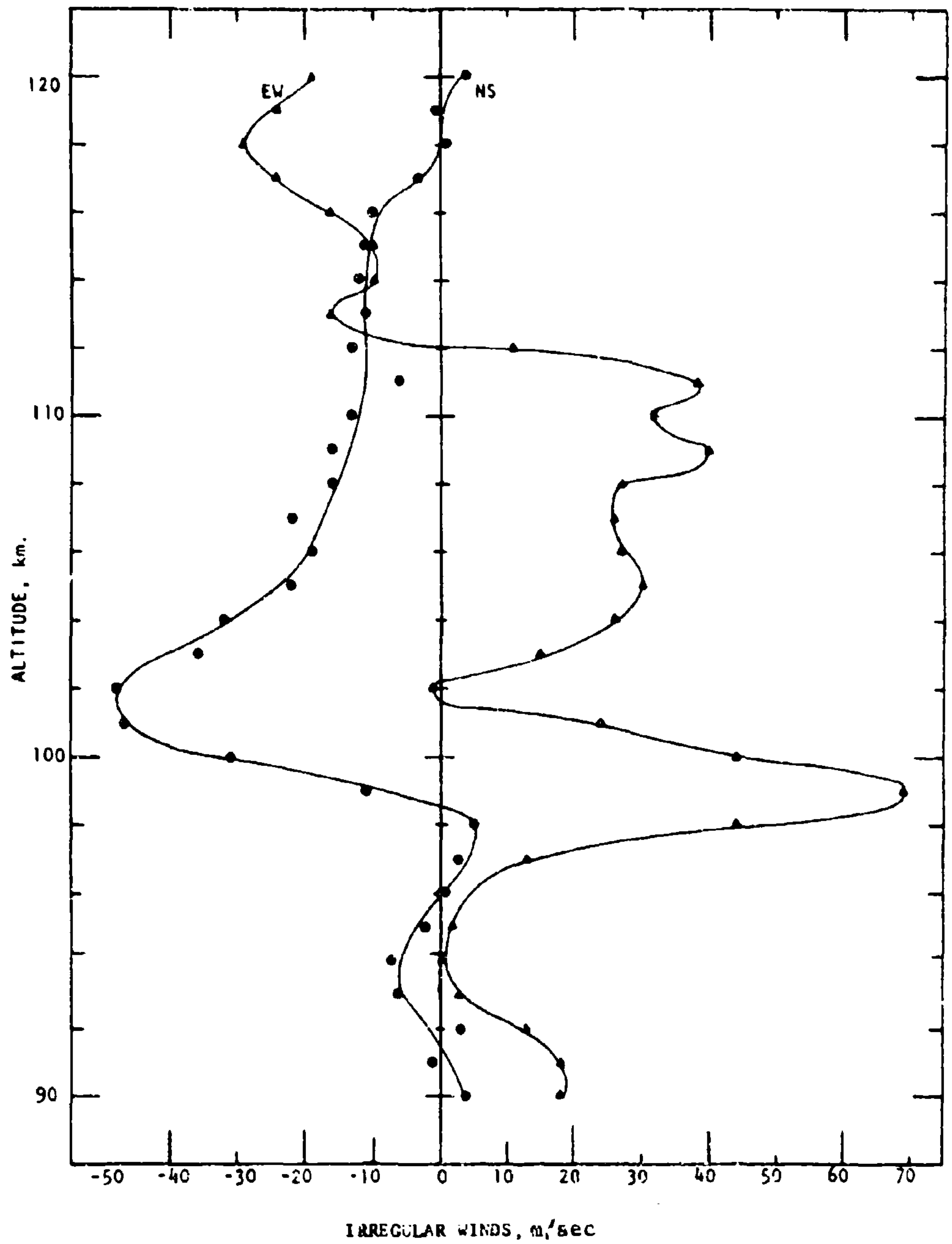


Figure 20. The Y17 Irregular Winds

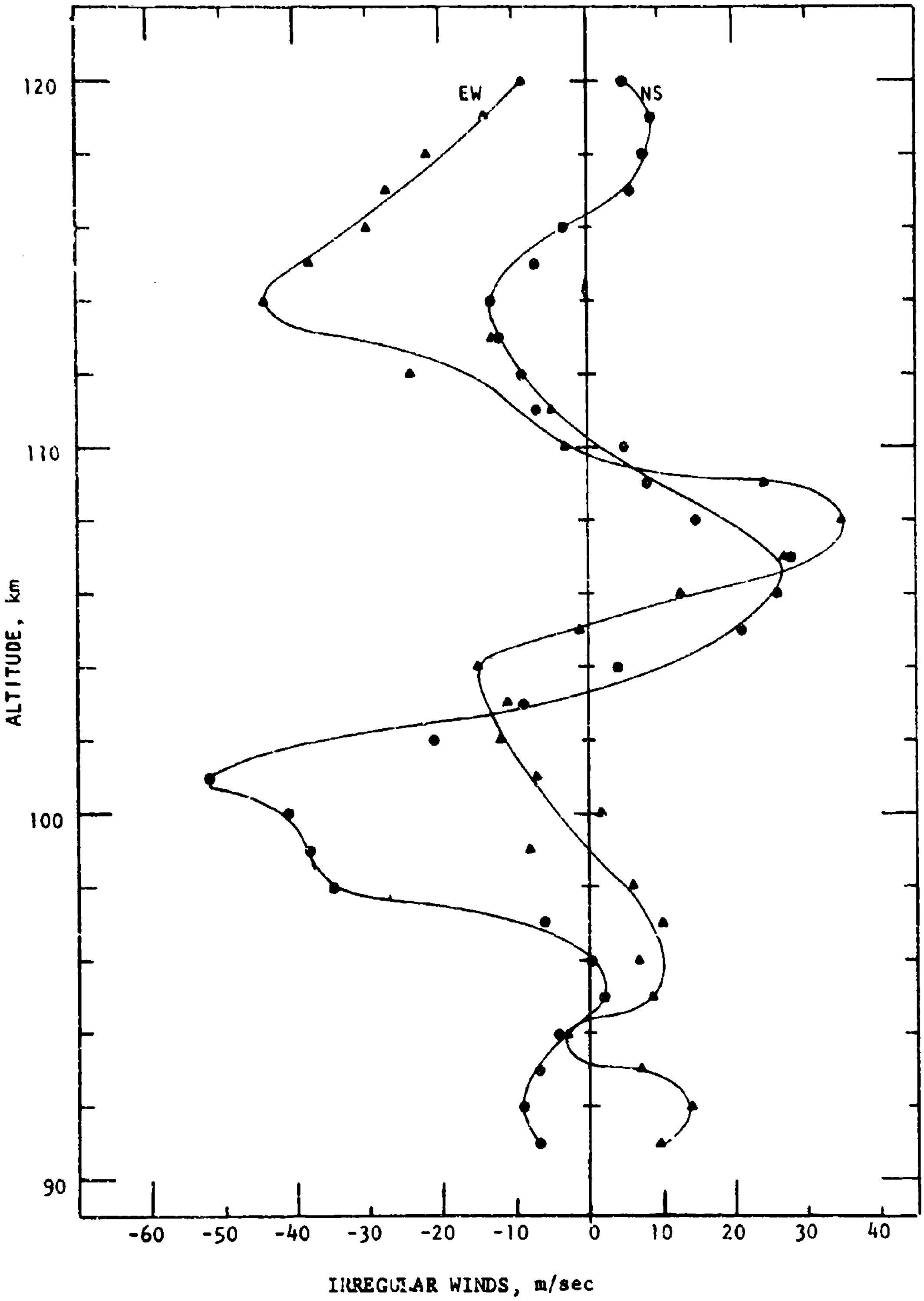


Figure 21. The Y18 Irregular Winds

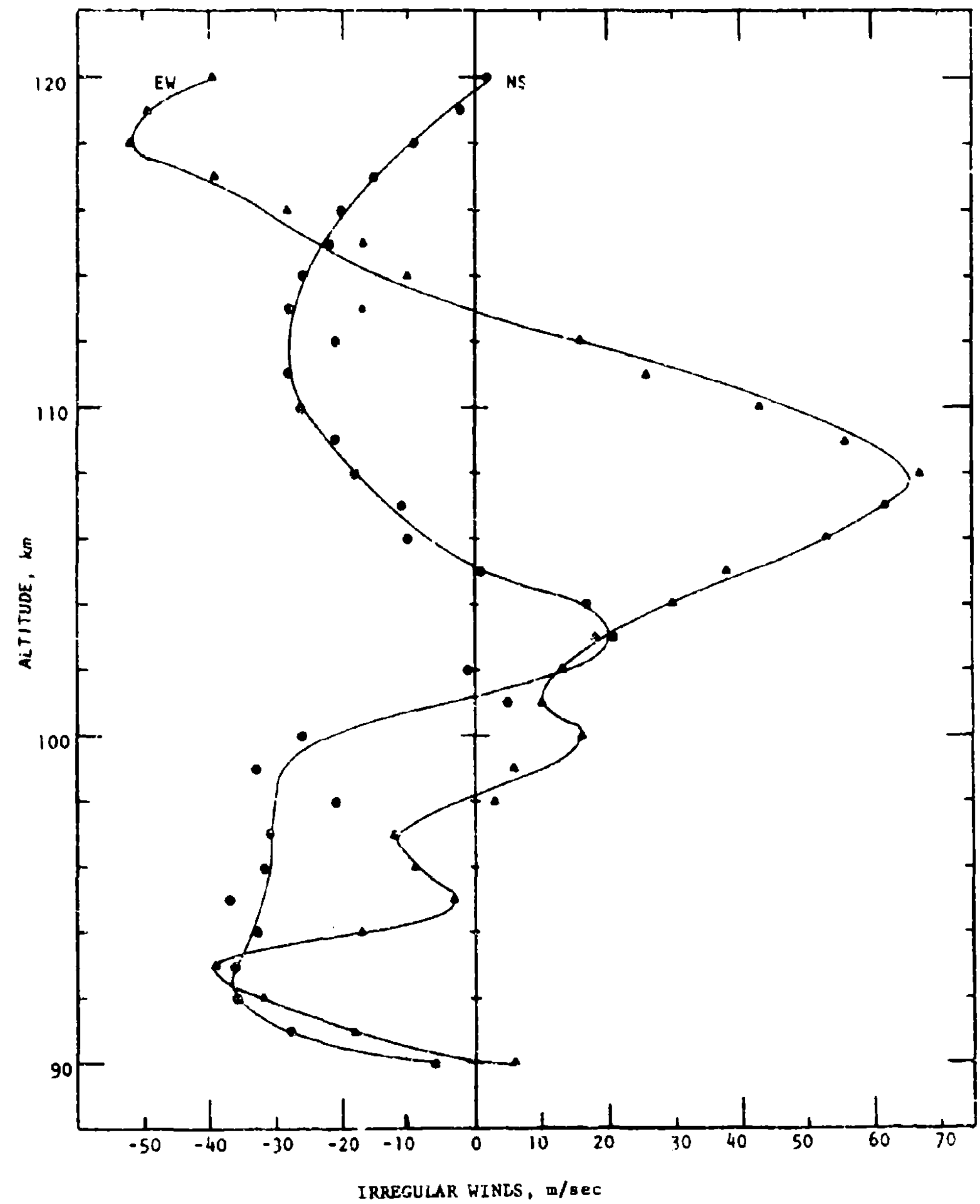


Figure 22. The Y19 Irregular Winds

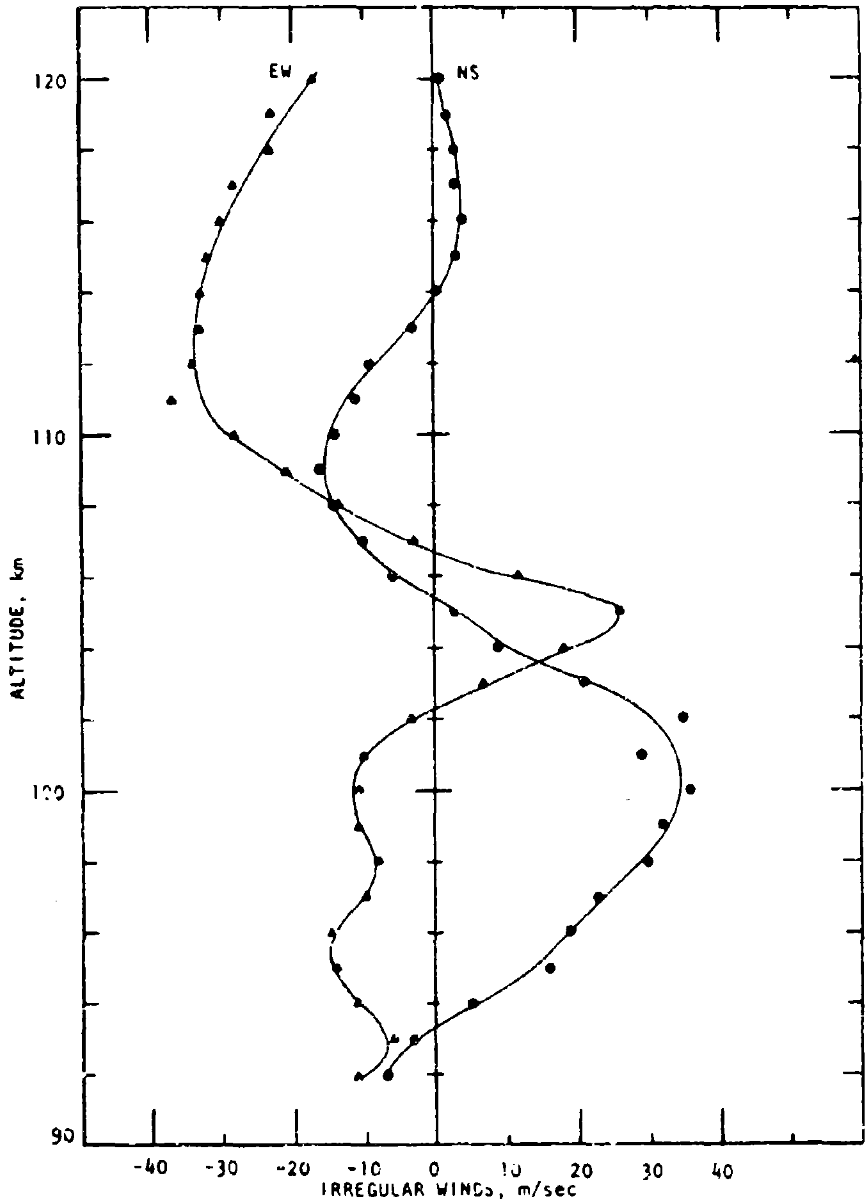


Figure 23. The Y20 Irregular Winds

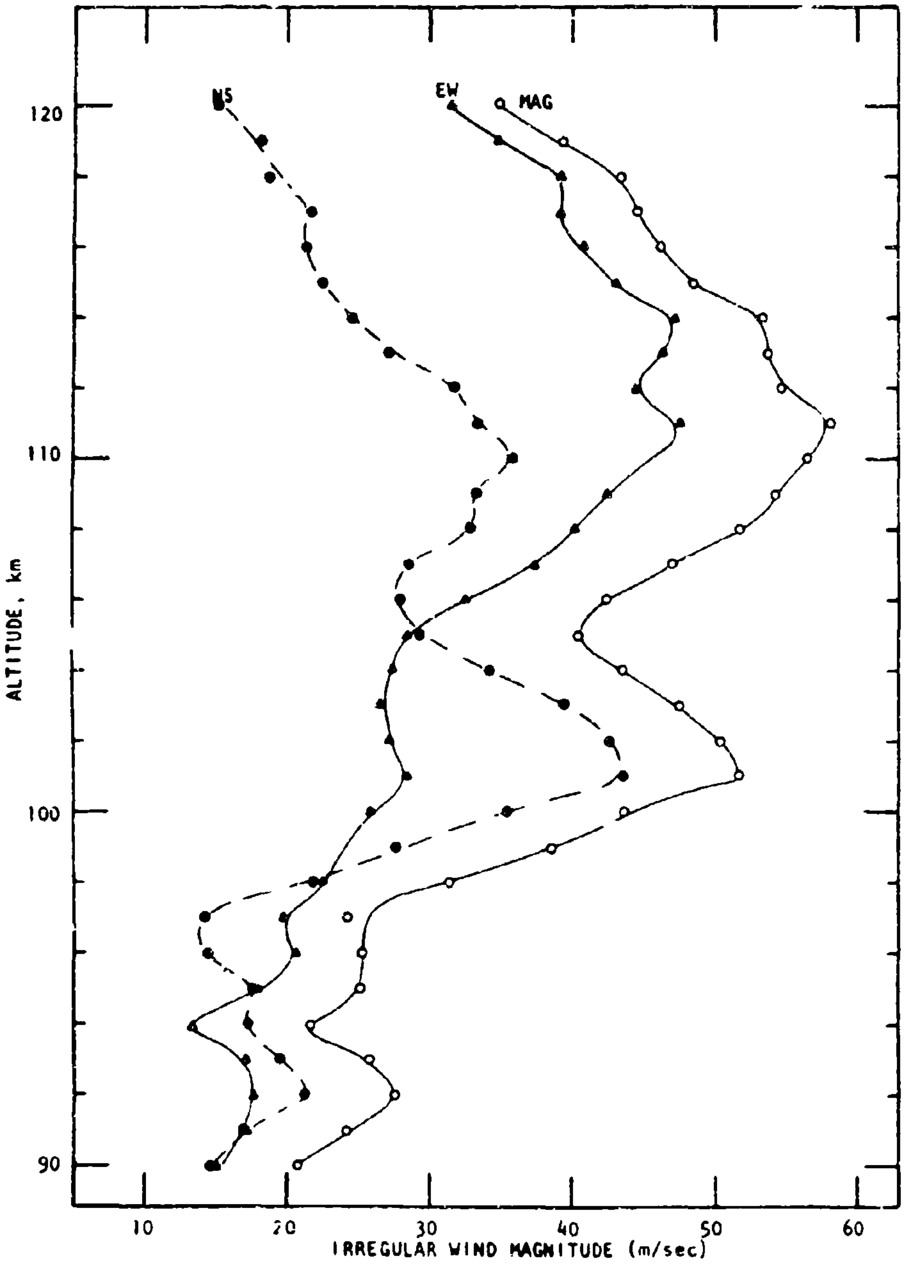


Figure 24. The rms Magnitude of the Horizontal Irregular Winds from the Y10-Y24 Series (Least Squares Residual Method)

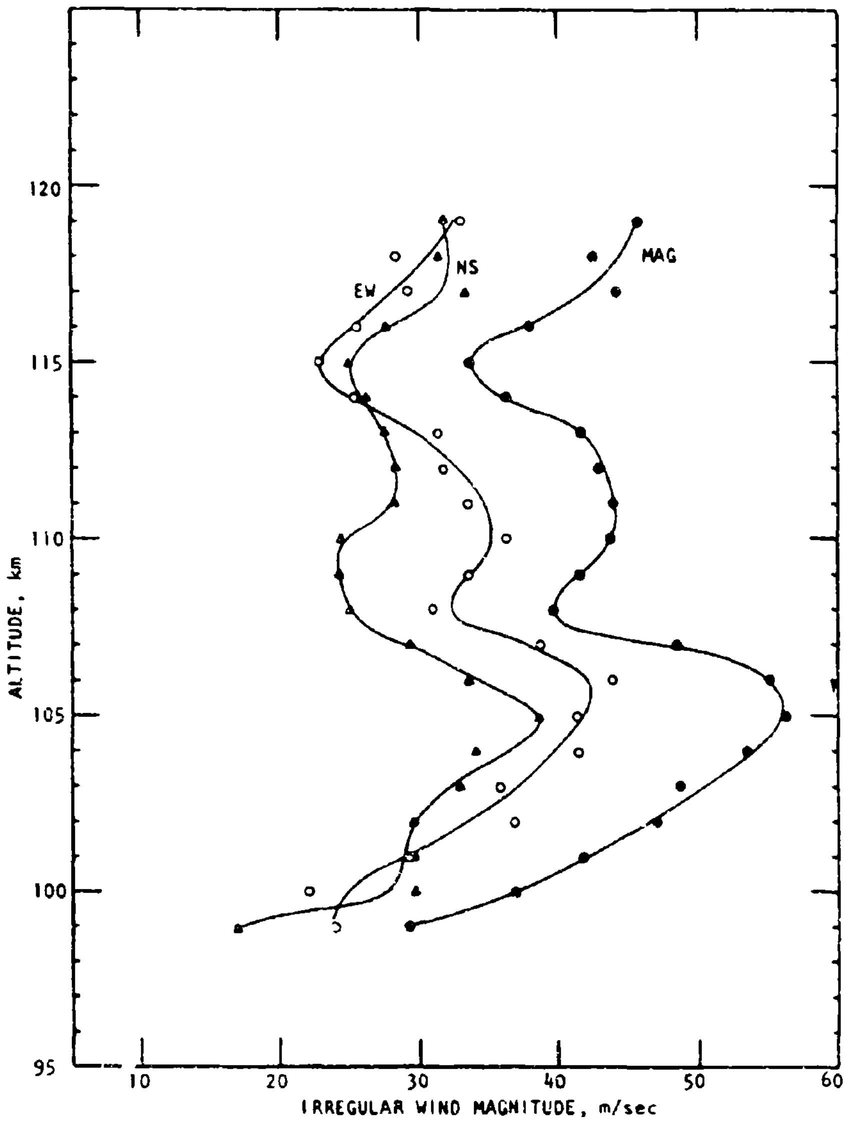


Figure 25. The rms Magnitude of the Horizontal Irregular Winds from the B30-B42 Series (Least Squares Residual Method)

TABLE III

IRREGULAR WINDS COMPUTED AS THE RESIDUAL WINDS AFTER THE SUBTRACTION OF TIDAL COMPONENTS, FROM THE Y-10 THROUGH Y-24 SERIES

SHOT Y-14

ALTITUDE (KM)	WIND COMPONENTS NORTH-SOUTH (M/SEC)	WIND COMPONENTS EAST-WEST (M/SEC)
90	6.4	-7.8
91	10.6	-0.8
92	-17.7	-1.6
93	-24.6	8.7
94	-21.3	-11.1
95	-20.4	-34.3
96	-13.3	-36.8
97	-4.6	-34.0
98	15.6	-39.3
99	36.6	-36.7
100	45.3	-24.8
101	40.3	-13.4
102	25.6	-4.8
103	5.2	0.4
104	-0.9	-3.9
105	8.1	-18.0
106	19.0	-35.6
107	36.2	-35.5
108	56.1	-22.7
109	62.1	-3.1
110	72.1	14.8
111	71.8	25.0
112	62.9	51.2
113	32.5	50.6
114	22.2	58.9
115	14.8	62.7
116	11.5	68.0
117	4.4	71.8
118	0.6	77.7
119	-1.2	71.2
120	2.0	63.1

SHOT Y-15

ALTITUDE (KM)	WIND COMPONENTS NORTH-SOUTH (M/SEC)	WIND COMPONENTS EAST-WEST (M/SEC)
90	-13.4	-5.5
91	-4.7	14.1
92	1.2	14.0
93	6.6	3.6
94	9.1	0.1
95	12.7	2.8
96	16.9	0.4
97	14.2	1.1
98	-15.5	15.1
99	-19.7	25.4
100	-33.2	23.5
101	-48.8	31.6
102	-65.2	39.1
103	-66.0	44.5
104	-54.2	31.7
105	-5.4	7.7
106	11.1	19.0
107	28.0	36.0
108	41.9	50.8
109	45.0	70.0
110	45.2	72.0
111	43.1	83.9
112	31.7	85.0
113	25.0	87.5
114	17.3	85.1
115	5.3	78.7
116	-5.9	74.4
117	-17.2	71.0
118	-26.4	64.9
119	-31.4	53.7
120	-23.8	39.3

TABLE III Continued

SHOT Y-16 ALTITUDE	WIND COMPONENTS	
	NORTH-SOUTH	EAST-WEST
(KM)	(M/SEC)	(M/SEC)
90	-4.6	-20.8
91	-10.5	-6.4
92	-14.0	-4.0
93	-13.8	-21.5
94	-12.3	-16.6
95	-13.8	-12.4
96	-16.1	-10.3
97	-15.8	-5.6
98	-14.2	0.5
99	-16.6	-28.8
100	-22.4	33.7
101	-40.0	22.2
102	-42.3	2.2
103	-13.7	7.6
104	13.6	20.4
105	20.0	37.7
106	29.2	57.3
107	29.7	76.0
108	16.8	83.2
109	-5.0	86.4
110	-15.5	68.3
111	-22.8	74.4
112	-32.4	58.2
113	-26.1	60.5
114	-33.4	51.9
115	-35.8	40.4
116	-32.9	36.3
117	-28.2	31.3
118	-23.3	24.7
119	-13.6	13.8
120	10.6	-1.6

SHOT Y-17 ALTITUDE	WIND COMPONENTS	
	NORTH-SOUTH	EAST-WEST
(KM)	(M/SEC)	(M/SEC)
90	3.8	17.7
91	-0.7	17.6
92	2.5	12.8
93	-5.6	3.1
94	-6.5	0.4
95	-2.3	1.5
96	0.8	0.4
97	3.4	12.7
98	5.4	44.4
99	-11.2	69.4
100	-30.5	44.1
101	-47.2	23.8
102	-48.0	-1.4
103	-36.0	14.9
104	-32.1	26.4
105	-21.8	30.2
106	-18.9	27.3
107	-22.2	25.7
108	-15.7	27.2
109	-15.9	39.5
110	-13.4	32.2
111	-6.4	38.0
112	-13.4	10.7
113	-10.5	-16.3
114	-11.5	-9.6
115	-11.3	-10.3
116	-9.6	-16.3
117	-3.1	-24.4
118	0.5	-28.8
119	-0.4	-24.1
120	4.4	-19.2

TABLE III Continued

SHOT Y-18

ALTITUDE (KM)	WIND COMPONENTS NORTH-SOUTH (M/SEC)	EAST-WEST (M/SEC)
91	-6.7	9.8
92	-8.7	14.0
93	-7.3	7.4
94	-3.9	-2.6
95	2.0	8.8
96	0.1	6.7
97	-6.3	9.6
98	-35.1	-5.7
99	-37.8	-7.6
100	-41.0	1.9
101	-51.8	-6.9
102	-20.9	-11.7
103	-9.3	-11.1
104	4.2	-14.9
105	21.0	-1.0
106	25.8	13.3
107	27.5	27.0
108	14.5	35.2
109	7.8	24.1
110	4.8	-3.1
111	-6.6	-5.2
112	-8.7	-23.5
113	-11.6	-13.2
114	-12.8	-43.7
115	-7.2	-38.3
116	-2.9	-29.8
117	5.7	-27.2
118	8.2	-2[illegible].7
119	8.9	[illegible].1
120	4.6	-9.3

SHOT Y-19

ALTITUDE (KM)	WIND COMPONENTS NORTH-SOUTH (M/SEC)	EAST-WEST (M/SEC)
90	-5.8	5.5
91	-28.3	-18.3
92	-36.4	-32.[illegible]
93	-36.0	-38.6
94	-33.0	-16.[illegible]
95	-36.7	-2.3
96	-32.1	-8.7
97	-30.7	-11.8
98	-20.9	3.7
99	-32.7	5.5
100	-25.9	16.0
101	5.2	10.3
102	-0.5	10.[illegible]
103	20.6	17.3
104	17.0	[illegible]
105	0.9	38.1
106	-10.4	[illegible].7
107	-11.3	61.8
108	-17.6	66.6
109	-21.1	55.9
110	-25.5	43.3
111	-28.4	26.5
112	-20.9	14.[illegible]
113	-27.6	-14.7
114	-25.8	-9.0
115	-21.6	-17.2
116	-20.0	-28.2
117	-15.1	-38.8
118	-8.9	-51.7
119	-1.7	-48.5
120	1.9	-38.5

TABLE III Concluded

SHOT Y-20

ALTITUDE	WIND COMPONENTS	
	NORTH-SOUTH	EAST-WEST
(KM)	(M/SEC)	(M/SEC)
92	-7.1	-10.7
93	-2.5	-5.5
94	5.3	-10.7
95	16.3	-13.9
96	18.7	-14.6
97	22.6	-9.6
98	30.4	-8.[illegible]
99	31.5	-11.3
100	35.6	-10.7
101	29.4	-10.1
102	35.3	-3.1
103	20.6	7.2
104	9.1	17.5
105	3.3	25.9
106	-6.2	12.2
107	-10.3	-2.6
108	-14.3	-14.2
109	-15.7	-21.4
110	-13.7	-28.0
111	-10.7	-37.2
112	-8.7	-34.[illegible]
113	-2.9	-33.2
114	0.1	-32.8
115	2.8	-31.6
116	3.8	-29.5
117	2.9	-28.3
118	3.0	-23.1
119	2.3	-23.4

those determined from the Y10 through Y24 series, in spite of the smaller number of releases in the B31 through B42 set.. However, because of the more restricted size of the data set, the tides and the individual profiles of residual winds determined from the B31 through B42 series were not considered sufficiently reliable to be included in this report.

The rms irregular winds have been evaluated by Woodrum and Justus (13) by taking the difference in winds between pairs of wind profiles from the same time of day with separations of from one to fifteen days. The differencing process eliminates the effect of such diurnally repeating winds as a steady mean wind, and the 24, 12, and 8 hour harmonic sequence of tides. The mean square of the irregular wind, v, is related to the mean squares of the wind difference from successive days, ΔV by the equation

$$\langle v^2 \rangle = \frac{1}{2} \langle \Delta V^2 \rangle \tag{6}$$

where the angle brackets denote an average. This same analysis was applied to several wind profiles obtained at Barbados at the same time of day and within a few days apart. The data were divided into 5-km altitude blocks, and the first and third quartile points of the velocity difference values found in that altitude range were computed. (The first quartile point is the value below which 1/4 of all the data lie, and the third quartile point is the value above which 1/4 of all the data lie.) The rms irregular wind was then computed from equation (6) by the mid mean process, which is an average of all data values falling between the first and third quartile points. These rms irregular winds versus altitude are shown in Figure 26. The first and third quartile points are indicated as the ends of the bars through the data points. These results are similar to those obtained by Woodrum and Justus (13) and are in good agreement with the rms irregular winds determined by the least square tidal analysis.

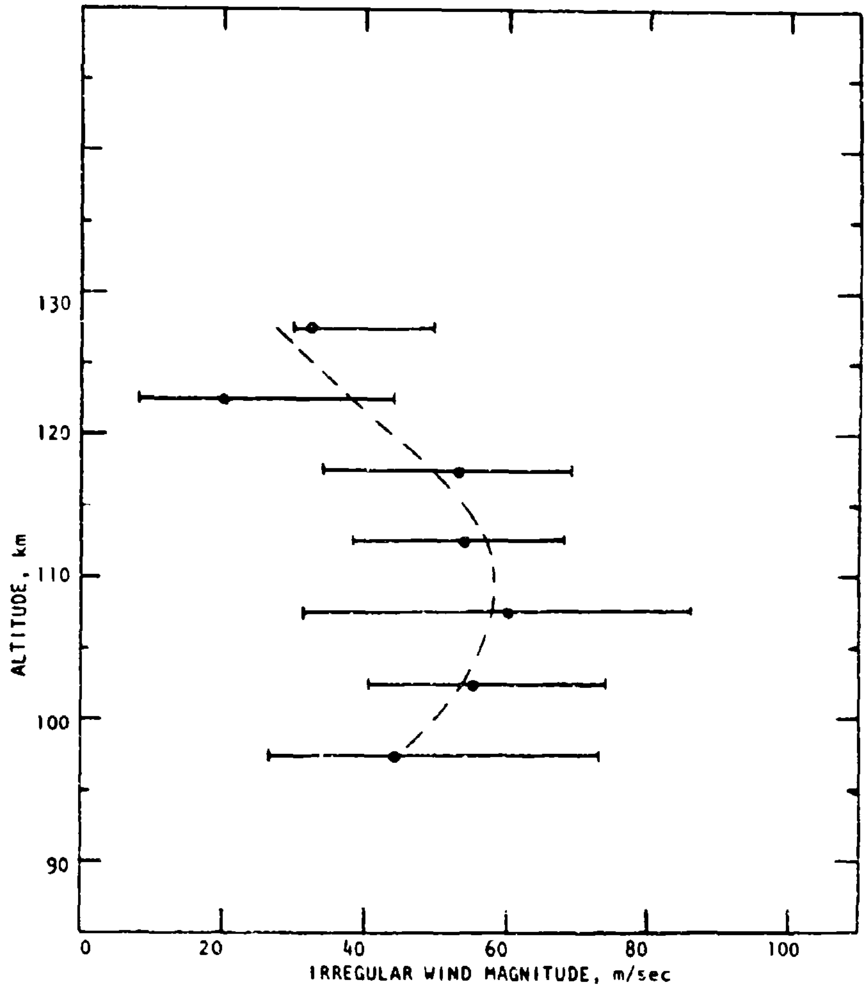


Figure 26. The rms Irregular Winds Computed from the Day-to-day Difference Method (Barbados Data)

c. Structure Function of the Irregular Winds. A function that is coming into frequent use in place of the correlation function is the structure function. The velocity structure function is defined as

$$D(\xi) = \left\langle \left[V(x) - V(x + \xi)\right]^2 \right\rangle \tag{7}$$

where V is a velocity component, x may be a space or time coordinate, and ξ is a space or time displacement. The angle brackets in equation (5) denote an average.

The profiles of irregular winds from the Y10 through Y24 series were divided into five pair-groups according to the time difference between the pairs of profiles. The irregular wind profile pairs were then differenced and averaged over altitude to compute the velocity structure function of the time variation of the irregular winds shown in Figure 27. These structure function data are observed to follow the power law

$$D(\Delta t) = \text{const.}\ (\Delta t)^{2/3} \tag{8}$$

indicated as the line through the data points in Figure 26. This 2/3 power law is usually thought to be associated with the inertial range of a continuous spectrum of turbulent winds. The observation of a 2/3 power law for the irregular winds may, therefore, indicate that the irregular winds have some of the characteristics of such turbulence, at least with respect to time variation.

Vertical structure functions of the irregular winds were also computed for each irregular wind profile by taking differences between values from the profile at altitudes different by the displacement amount and averaging over the profile. The average of the vertical structure function obtained from the irregular wind profiles from the Y10 through Y24 series is shown in Figure 28. This figure shows that the vertical structure function follows a power law given by

$$D(\Delta z) = \text{const.}\ (\Delta z)^{1.4} \tag{9}$$

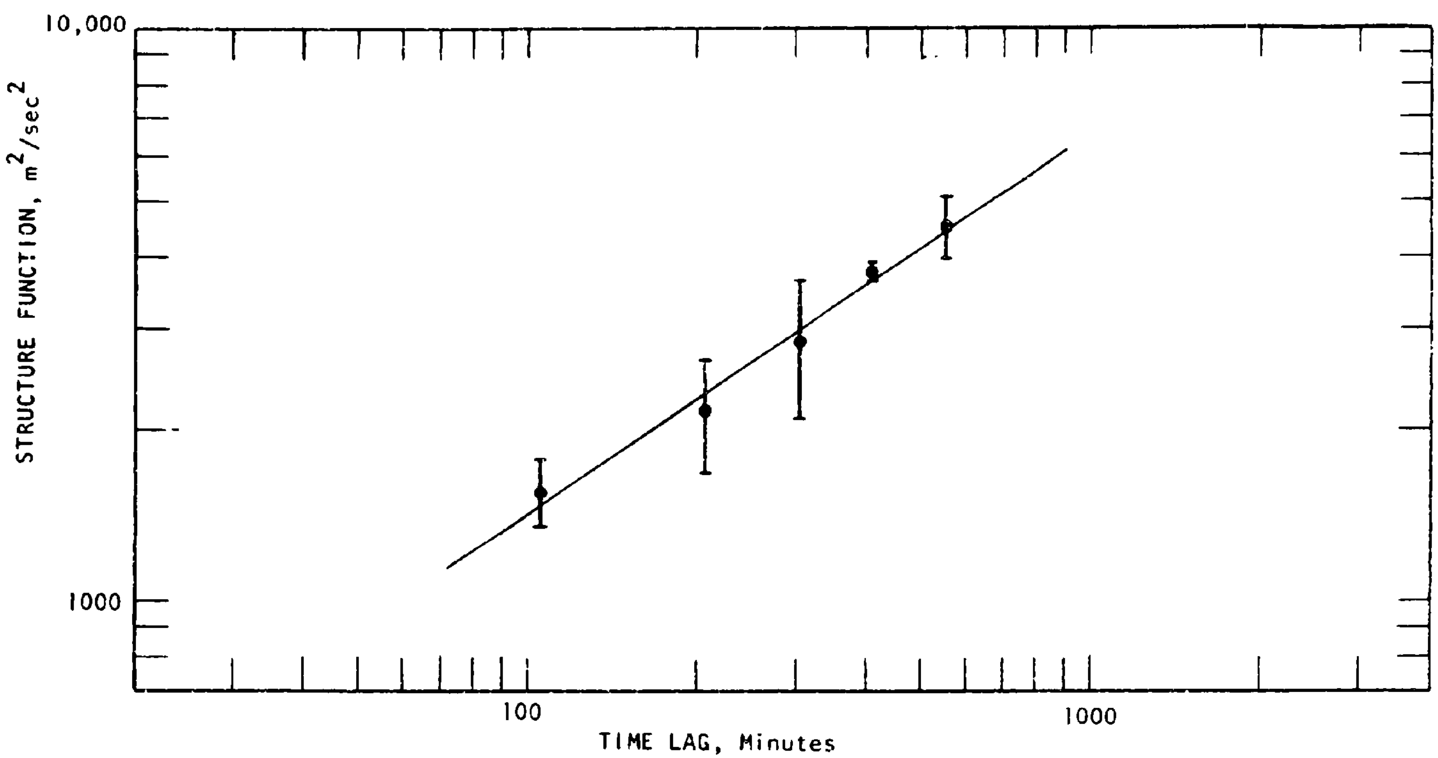


Figure 27. The Structure Function of the Time Variation of the Irregular Winds of the Y10-Y24 Series

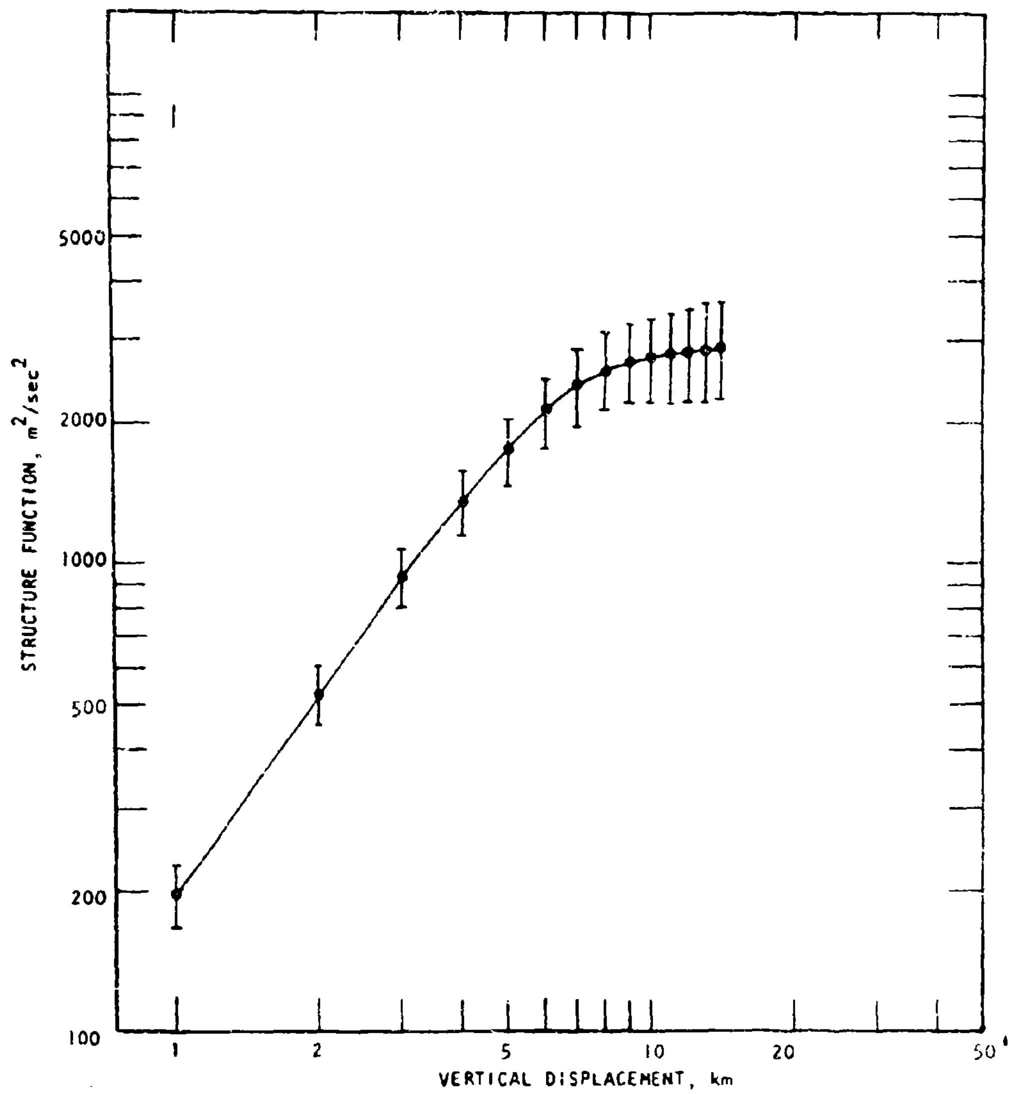


Figure 28. The Structure Function of the Altitude Variation of the Irregular Winds of the Y10-Y24 Series

over small vertical displacement Δz. The computed probable error in the expondnet of this power law variation is 0.1. The flattening off of the vertical structure function at large vertical displacements indicates a vertical scale for the irregular winds of about 10 km.

The horizontal structure function of the irregular winds can be estimated by taking differences in horizontal winds determined from up and down leg trails. The horizontal separation of the trails provides the horizontal displacement in the structure function computation. Several such structure function values have been calculated from up and down trails from Barbados and Yuma. These are plotted in Figure 29 together with some similar data obtained from Eglin releases (Justus (14)). Since the characteristic velocity of the irregular winds is 40 to 50 m/sec as seen from Figure 24, and since the time structure function indicates a characteristic time of several hundred minutes, then the horizontal scale (≈ characteristic velocity times characteristic time) must be of the order of 1000 km. Therefore, the horizontal structure function must approach the large X shown at the upper right of Figure 29. The line through the data points represents a horizontal structure function variation according to the power law

$$D(\Delta x) = \text{const.}\ (\Delta x)^{2/3} \tag{10}$$

and is seen to be in reasonable agreement with the observed data.

It should be noted that each data point was computed from a single up and down trail pair and the points were plotte versus mean separation. No attempt was made to restrict the data to a common altitude range or to subdivide the up and down trail data according to intervals or horizontal separation. As more up and down trail releases are made, it is expected that sufficient data will become available to make these more sophisticated analyses.

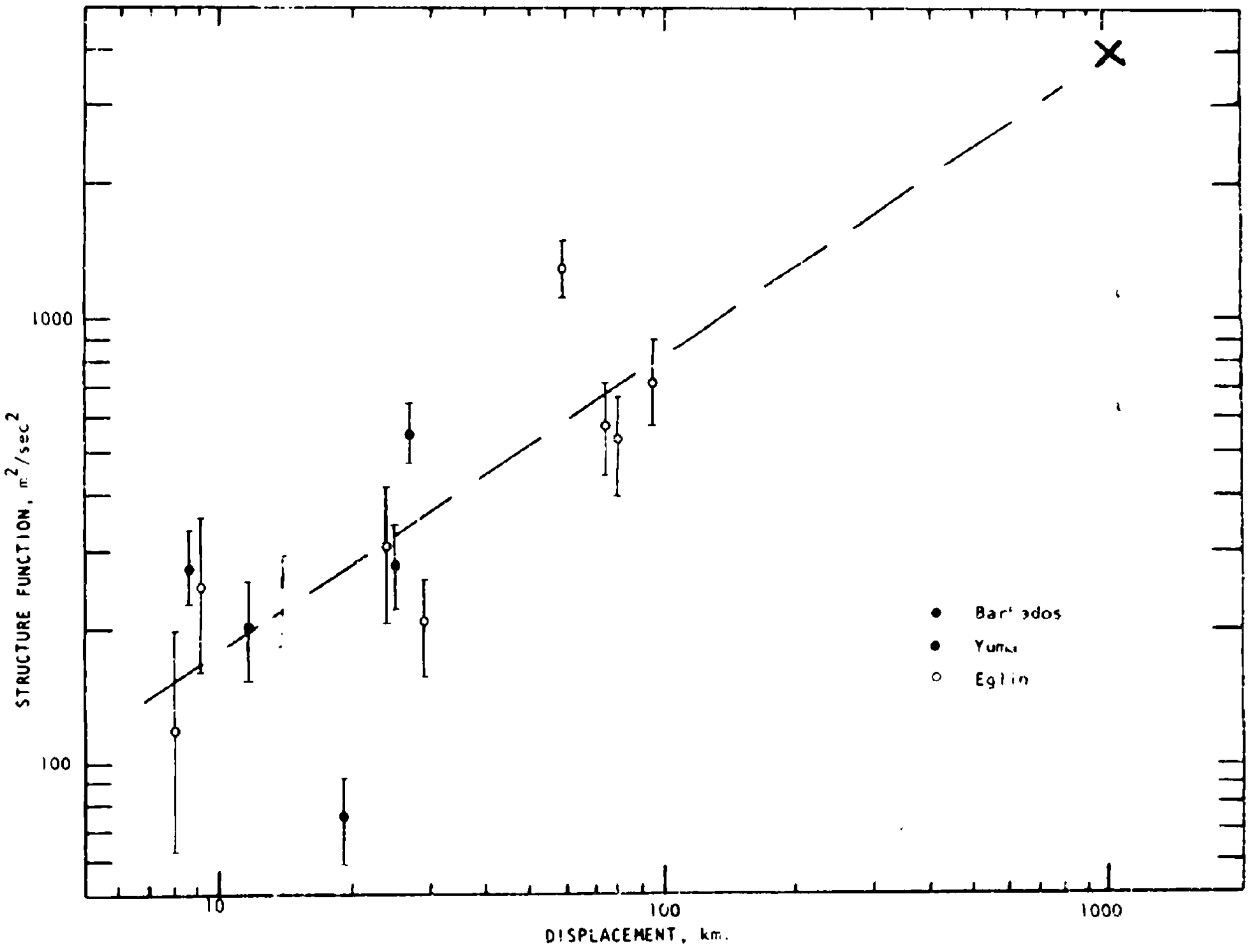


Figure 29. The Structure Function of the Horizontal Variation of the irregular Winds Computed by the Up and Down Trail Difference Method

SECTION V

SUGGESTIONS FOR FURTHER STUDY

1. The determination of vertical winds by the chemical release technique requires cloud features that can be identified and tracked. The best technique for obtaining large amounts of clearly defined cloud structure suitable for vertical winds analysis is to release cesium at twilight and to photograph it with infrared film, which is sensitive to the infrared resonance line of the cesium vapor. Cesium nitrate can be released in trail form similar to the more widely used sodium trails. In the past cesium releases (usually in the form of a single-point release) have been employed primarily for communication studies and other projects that require high electron yields of an ionizable payload material. Even from these less-than-ideal release forms, many vertical winds have been obtained (Edwards, et al (15)). Much more would be learned about vertical winds, irregular winds, and turbulence if cesium trail releases were used in a project designed primarily to obtain wind information.

2. Because this effort was a pilot study, only an incomplete analysis could be made of some of the results presented here. Additional information about the tides and irregular winds could undoubtedly be obtained from a more thorough analysis of existing chemical release data, including that which was presented here in initial form.

3. Three particular types of release programs were found quite fruitful in the study of irregular winds, and more of these kinds of releases are desirable. These are (1) sequences of many releases throughout the night for several successive nights; (2) releases with up and down trails for the study of horizontal wind differences; and (3) releases made at the same time of day on successive days. Since on the basis of the present study it is felt that at least 12 releases spread over two or three nights would be required for

least squares harmonic analysis to determine tides and residual irregular winds, perhaps more emphasis should be placed on the up and down and day-to-day difference type of releases than has been done in the past. Because these releases can be of value even when they occur one at a time with irregular spacing in time, these types of releases would be more economical than the long sequence of closely time spaced releases. However, as this pilot study has shown, the best and most definitive results can be obtained from the long sequence of releases.

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APPENDIX A

THE SINGLE-SITE TECHNIQUE

The single-site technique presumes that a cloud point can be tracked for several times from a single observing site and that the initial position of the point is known by some means. Figure A-1 illustrates the geometry of the single-site technique. The cloud point, assumed to move linearly with constant velocity, would be located in space at a sequence of positions labelled S_1 through S_5 at a sequence of equally spaced times t_1 through t_5. The image of the cloud point would be located at a sequence of film positions labelled F_1 through F_5. The orientation of the line along which the cloud image points move on the film (measured by the angle α) can be used to determine the plane in which the various lines of sight lie (the OS_1S_5 plane). The spacing versus time of the film points F_1 through F_5 can be used to compute the angle β which uniquely places the line S_1S_5 in space, since the position S_1 is assumed known. The orientation of the line S_1S_5 gives the wind direction, and the distance between the S_1 through S_5 points versus time gives the wind speed.

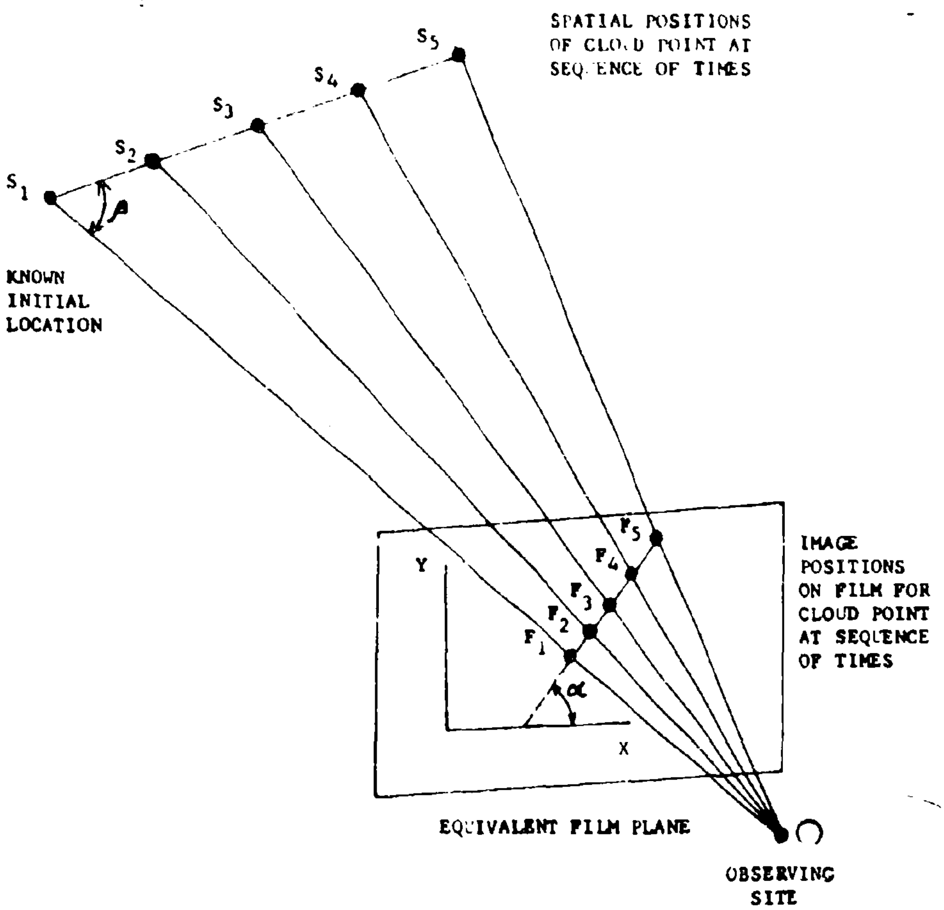

Figure A-1. The Geometry of the Single Site Technique for a Point Observed at Five Times.

APPENDIX B

AMPLITUDES (A'S) AND PHASES (ϕ'S) COMPUTED FOR THE 24, 12, AND 8 HOUR PERIOD TIDES ACCORDING TO EQUATION (5). AMPLITUDES ARE IN M/SEC AND PHASE ANGLES IN DEGREES.

TABLE B-1

AMPLITUDES AND PHASES OF THE 8-HOUR TIDAL COMPONENT

Altitude	N-S Amplitude	N-S Phase	E-W Amplitude	E-W Phase
90	3.89	60.80	6.71	294.66
91	10.69	100.78	5.39	31.33
92	12.26	78.23	12.24	38.37
93	8.73	108.02	10.57	69.51
94	9.22	130.60	4.73	103.45
95	11.11	137.55	5.60	181.02
96	10.90	146.60	6.64	173.95
97	12.73	147.18	8.39	171.77
98	18.78	149.61	12.17	186.13
99	18.18	136.11	9.46	197.86
100	14.57	133.33	15.85	196.49
101	9.91	149.04	12.89	189.83
102	9 40	163.30	11.85	189.22
103	3.55	220.43	11.04	194.16
104	7.22	338.05	12.09	209.74
105	15.13	356.21	12.34	236.57
106	21.62	6.11	15.66	278.08
107	19.87	7.5[illegible]	21.21	61.26
108	18.05	21.45	24.02	304.48
109	14.29	29.79	18.20	237.79
110	12.17	43.67	23.31	331.57
111	11.35	58.69	30.05	345.55
112	8.71	87.37	27.41	358.33
113	10.09	72.10	42.07	5.18
114	9.02	93.81	36.50	11.22
115	9.10	123.34	33.73	16.72
116	10.11	136.20	33.33	22.02
117	10.21	150.67	34.62	27.16
118	19.98	185.17	33.30	36.70
119	13.51	169.77	29.44	40.45
120	10.94	165.71	26.81	46.36

TABLE B-11

AMPLITUDES AND PHASES OF THE 12-HOUR TIDAL COMPONENT

Altitude	N-S Amplitude	N-S Phase	E-W Amplitude	E-W Phase
90	16.09	96.06	6.55	82.98
91	17.34	106.76	11.12	86.91
92	20.39	97.89	19.76	80.68
93	16.28	117.04	27.74	98.92
94	10.27	138.55	26.59	108.64
95	6.69	189.46	21.44	120.87
96	7.71	223.42	16.76	129.67
97	7.96	218.88	14.94	137.98
98	9.12	192.67	13.38	163.05
99	7.47	159.62	9.92	192.22
100	3.57	197.93	13.33	201.56
101	4.95	255.96	11.25	210.44
102	7.35	255.02	11.99	234.85
103	10.00	286.26	15.60	255.52
104	14.15	313.28	21.97	265.56
105	21.51	320.09	27.79	274.54
106	22.51	335.60	29.96	285.29
107	17.14	355.99	29.25	295.51
108	16.20	39.49	25.52	302.20
109	18.33	67.21	22.97	319.24
110	21.39	84.64	19.59	337.49
111	23.93	92.87	21.70	359.47
112	25.56	106.59	20.31	32.12
113	20.99	95.19	28.42	35.98
114	20.74	103.10	28.79	46.83
115	18.70	112.31	31.05	57.90
116	18.69	116.70	33.90	63.74
117	17.53	122.42	37.90	68.65
118	16.62	129.63	42.25	75.47
119	15.20	135.80	41.66	79.77
120	14.36	133.03	40.72	84.08

TABLE B-III

AMPLITUDES AND PHASES OF THE 24-HOUR TIDAL COMPONENT

Altitude	N-S Amplitude	N S Phase	E-W Amplitude	E-W Phase
90	27.86	25.74	26.00	0.88
91	21.58	51.96	27.54	357.09
92	21.98	144.07	21.05	10.40
93	26.63	165.65	19.64	32.31
94	34.21	184.53	17.42	60.79
95	42.72	198.56	22.42	112.56
96	48.33	204.44	35.72	126.81
97	50.24	212.24	38.58	137.84
98	52.82	225.54	44.08	164.61
99	45.02	235.04	53.07	194.40
100	36.79	254.23	67.09	202.25
101	20.81	282.77	76.22	213.71
102	13.72	314.41	83.03	226.17
103	23.15	340.31	87.79	238.94
104	30.44	345.74	92.22	250.62
105	24.22	2.37	96.20	266.30
106	28.02	8.62	102.32	278.03
107	35.77	8.20	112.73	287.18
108	41.82	25.34	117.92	291.91
109	48.94	44.34	116.64	296.92
110	55.92	53.58	93.60	308.06
111	57.01	59.07	91.19	316.73
112	59.43	67.23	77.14	333.27
113	53.34	80.01	67.17	353.25
114	55.13	84.80	57.89	348.34
115	54.70	90.73	48.27	351.18
116	54.76	92.72	42.30	351.16
117	48.08	95.01	35.31	358.70
118	41.86	98.52	29.00	0.40
119	34.70	102.31	18.65	13.96
120	18.31	91.88	17.88	76.74

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13. ABSTRACT

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Results are presented of a study of the irregular horizontal and vertical winds observed from chemical clouds released on 16-19 November 1966 from Yuma, Arizona; on 17 November 1965 from Barbados, West Indies; and on 17 May 1963 from Eglin Air Force Base, Florida. The vertical wind data showed that vertical motion does not occur in such a way that as cloud points move up or down they would tend to alter their horizontal motion so as to adjust to the mean wind profile. It was found, however, that the horizontal wind profiles tended to change with time in such a way that the altitudes of constant speed would shift up or down in a similar manner to the vertical movements of cloud points. The altitude variations of constant speed points throughout the nights of 16-17 and 18-19 November at Yuma were found to be smaller in magnitude than the vertical motions of the cloud points over short periods. The 24, 12, and 8 hour period tides were computed for the 16-19 November 1966 Yuma data. Tidal winds and the irregular horizontal residual winds are reported. The rms irregular winds computed by a day-to-day difference method are also presented. Structure functions of the horizontal irregular winds exhibit a 2/3 power law with respect to both time variation and horizontal displacement. However, the vertical structure function of the horizontal irregular winds is found to follow a power law with an exponent value of 1.4. Some suggestions for further study are given.

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